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PANEL SYSTEM OF COAL MINING
A GRAPHICAL STUDY OF PERCENTAGE OF EXTRACTION

BY

C. M. YOUNG

ILLINOIS COAL MINING INVESTIGATIONS COÖPERATIVE AGREEMENT

(THIS REPORT WAS PREPARED UNDER A COÖPERATIVE AGREEMENT BETWEEN THE
ENGINEERING EXPERIMENT STATION OF THE UNIVERSITY OF ILLINOIS,
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ENGINEERING EXPERIMENT STATION

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PANEL SYSTEM OF COAL MINING
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PANEL SYSTEM OF COAL MINING
A GRAPHICAL STUDY OF PERCENTAGE OF EXTRACTION

I. Introduction

1. *Reasons for the Investigation.*—In 1917 an investigation* of the percentages of coal extracted and lost in Illinois and in other bituminous coal mining districts showed that the percentage obtained is less than is commonly believed. The conclusions reached in the earlier investigation naturally led to the study of the panel system to determine the greatest possible extraction with different dimensions of workings.

2. *Other Investigations.*—Investigations of a similar nature have been made to determine the relation between dimensions of workings and amounts of extraction. Special mention should be made of the work of J. C. Quade, G. E. Lyman, and J. C. Gibson, whose methods are described on pages 46, 66, and 70. So far as is known, however, no study of the panel system in general with regard to the percentage of extraction and the change of this percentage with change of dimensions of workings has hitherto been made.

3. *Acknowledgments.*—The work of the Illinois Coal Mining Investigations is carried on under the direction of Professor H. H. Stoek, head of the Department of Mining Engineering, University of Illinois; F. W. De Wolf, Chief, State Geological Survey Division; and G. S. Rice, Chief Mining Engineer, U. S. Bureau of Mines. Professor Stoek has been especially helpful in carefully revising the manuscript.

4. *Summary.*—The investigation shows that the highest extraction which can possibly be attained under the conditions assumed, with rooms 300 feet long and 30 feet wide on 50-foot centers, is only 57.05 per cent. Even if the improbable ratio of room to pillar width

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*Young, C. M., "Percentage of Extraction of Bituminous Coal with Special Reference to Illinois Conditions." Illinois Coal Mining Investigations, Univ. of Ill. Eng. Exp. Sta., Bul. 100, 1917.

of 4 to 1 (40-foot rooms on 50-foot centers) is assumed, the highest attainable extraction is 68.48 per cent. No better results than these can be reached unless the amount of coal left in room pillars or in barrier pillars is reduced. As a matter of fact, the average extraction throughout the State is not more than 50 per cent and in those parts where coal is thickest and lies at greatest depth, the extraction will not average so much. The lowest extractions are due in part to the leaving of top coal; thus the actual extraction in some districts is lower than that indicated by calculation on an area basis.

The percentage of extraction increases with the increase of ratio between room width and pillar width, with length of rooms and with number of rooms per entry, but the diagrams showing the effect of changes of dimensions on percentages of extraction indicate that, except in the case of ratio of room width to pillar width, very nearly the maximum effect of these changes has been reached by the dimensions considered, *i. e.,* room length from 200 to 300 feet, room width from 20 to 40 feet, number of rooms per entry from 8 to 24. Further increase of length of rooms or of number of rooms per entry would not materially increase the percentage of extraction.

The percentage of extraction could be further increased by increase of room width in relation to pillar width, but it is only rarely that a ratio of even 4 to 1 can be used without the production of squeezes. The conclusion is, therefore, warranted that the extraction under a panel system of mining, which relies upon coal left in the ground for the support of the overburden, cannot be greater than about 68 per cent unless a smaller amount of coal is left in the form of barrier pillars than is assumed in this investigation.

5. *Reasons for Low Extraction.*—There are two essential reasons for low extraction. The first is the leaving of top coal, because the roof needs support or because the bed is too thick for convenient mining of the whole thickness. Such losses occur principally in the thick coal of the southern part of the State. When some support for the roof is necessary and when it can be furnished by coal left in place at less cost than by artificial means, the leaving of coal is justified, commercially, though such loss may still be criticized from the standpoint of conservation. In some places, however, the thickness of coal left is much greater than is necessary to support the roof, and it is probable that a considerably larger amount of the coal might be extracted at a cost which would allow a profit on the top coal mined.

The second reason for low extraction lies in the method of mining which depends upon coal, left in the form of pillars, to support overlying material. The use of coal for such support may be considered: first, for the support of the immediate top until a place has been worked out, and secondly, for the permanent support of the overburden to prevent subsidence of the surface.

In the first case large pillars would commonly be unnecessary and the ratio of room width to pillar width might be large. Under this case may be considered such operations as those in Fulton County, discussed in Appendix I, where no attempt is made at permanent support of the surface, and where coal left in pillars may be considered as serving the same purpose as props. Pillars which are 8 feet wide near the entry are tapered to almost nothing at the end; yet these pillars serve their purpose of support to the immediate top until the coal has been worked out. Under such circumstances it is possible to extract from 70 to 80 per cent of the coal, but such results would be unattainable in thick coal because the strength of a pillar decreases rapidly as its height increases, and consequently greater pillar width would be necessary to furnish the support needed.

The second case is that of the use of coal in the form of pillars as a permanent support for the overburden, and this use constitutes the principal reason for low extraction. A much higher percentage of coal might be obtained if the surface were allowed to subside. Under present conditions, however, this practice is not often considered practical, especially where ownership of the coal and the surface is separate, because the operator is often compelled to pay very high damages for any disturbance of the surface.

While no general rule can be stated for the determination of the dimensions of pillars and of the ratio of pillar area to room area necessary for the permanent support of the surface at a given depth, it is known that the relative area of pillars must be made greater as the depth increases. Experience in Illinois shows that the surface cannot be permanently sustained over the deeper and thicker beds of the State unless about half of the coal is left. This statement is true in general for Districts V, VI, and VII, of the Illinois Coal Mining Investigations, which include bed 5 in Saline and Gallatin counties and nearly all mines in the No. 6 coal.

No high percentage of extraction is possible without subsidence of the surface unless the space left by the coal is filled, probably by washing fine material into the mine through pipes. Illinois mines are in general nearly level and it would be difficult to transport the filling material along the entries by means of water; also the removal of the water would be difficult and expensive. For these reasons the method appears at present to be impractical in Illinois; therefore if high extraction is to be obtained subsidence must be expected and controlled as is being successfully done in some districts where extraction of more than 90 per cent is customary.

II. ADVANTAGES OF GREATER EXTRACTION

The principal advantages of higher extraction may be summarized as follows:

6. *Investment per Ton of Total Output.*—If the amount of coal extracted could be increased from 50 to 100 per cent, the investment, per ton of total coal produced for surface plants, shafts, entries, etc., would be reduced by half because twice as much coal would be handled with the equipment. Maintenance charges, however, would not be similarly reduced since the colliery would be in operation for twice as long if the same territory were involved. The cost per ton of coal in the ground would be decreased by one-half when the coal is purchased in fee, and where it is leased on royalty the owner of the land would receive twice as much as he formerly received.

7. *Cost of Haulage.*—The cost per ton for moving the coal from the working place to the shaft would be decreased, because the average length of haul would be only half as much as with 50 per cent extraction. Twice as much coal would be hauled through the entries, so that the cost per ton of coal for maintaining entries would be lessened. Since the element of time is also involved, it is not possible to say that the cost for maintenance would be reduced by 50 per cent.

8. *Cost of Ventilation.*—The average distance from the shaft of places to be ventilated being only half as much as with 50 per cent extraction, the expense of ventilation would be decreased. Ventilation would be simplified, because worked-out places would cave and would require no attention except the provision of bleeders or of seals.

To summarize, the cost per ton of total coal for all installations and excavations which would not need renewal because of the increased time of service would be reduced by 50 per cent. In operations whose costs are affected by the distance from the shafts to the point of production, the costs would be reduced in proportion to the effect of the distance. While it cannot be expected that an extraction of 100 per cent will be obtained, an extraction of 90 per cent should not be difficult from an engineering standpoint, and the economies resulting would be in proportion to the increase.

9. *Efficiency of Supervision.*—Appreciation of the need of thorough supervision to preserve mines in working condition and to prevent accidents is increasing, but under present mining practice the visits to a working place can be made more frequent only by increasing the supervising force, thus adding to the cost of coal. With greater extraction the concentration of workings would eliminate a part of the time now lost in travel, and thus would help to solve the problem of increased supervision.

10. *Prevention of Waste.*—The greatest ultimate advantage of higher extraction would be the increase of the available reserves of coal. At present this advantage is largely overlooked, because the reserves of coal of the quality and thickness now mined are sufficient for many years. Unfortunately, however, it is the best coal and that easiest to produce which is being lost, and the coal which will be available when the reserves are exhausted will certainly be more costly and perhaps not so good. Even if the question of reserves is neglected because no immediate exhaustion is possible, it is a subject for great regret that a substance as valuable as coal should be unnecessarily lost.

There is no doubt of the ability of mining engineers to plan operations to get high extraction. The methods are well known and are employed with great advantage and without great difficulty in some districts, and there is no reason to doubt their success in Illinois. The problem is more one of immediate commercial advantage than one of engineering practice.

III. PRINCIPLES INVOLVED IN HIGH EXTRACTION

High extraction requires the mining of pillar coal. Three principles are involved in the successful extraction of this coal: first, the strain on the roof above the rooms must not be great enough to cause the roof to fall before the pillar coal is removed; secondly, the strain on the pillars must not be great enough to cause squeezing; thirdly, additional strain on the pillars, due to pillar drawing, must be prevented by the breaking of the roof behind the retreating pillar face.

The fall of the roof can be prevented by making the room sufficiently narrow, or at least the strain can be decreased so that proper timbering will prevent falls. This does not necessarily involve low ratio of room width to pillar width. If the pillars are to be removed, however, they will necessarily be made large enough for convenient working. In some districts where pillar coal is successfully mined and where high extraction is reached, rooms are made very narrow and are, in fact, little more than openings for ventilation and for access to the pillar coal. Such extreme narrowness is necessary only under bad top, and rooms in most places in Illinois could probably be made 20 feet wide without interference with successful pillar work.

The strain on the pillars due to the weight of the overburden must be kept within the limits of strength of the pillars themselves and of the top and bottom. When the room coal is removed, the weight of the overlying material is transferred to the pillars and these must be made large enough to stand the strain without being crushed or pressed into the top or bottom.

When the extraction of the pillar coal is commenced at the end of the room, a part of the weight of the overburden above the portion removed is transferred to the remaining pillars, thus increasing the strain. This strain may be relieved by the breaking of the roof behind the retreating pillar face.

If enough coal is left in pillars to prevent crushing before pillar drawing begins, and if the strain is relieved by the breaking of the roof during pillar drawing, squeezes will be entirely prevented.

These three principles: rooms narrow enough for the support of the roof, pillars large enough to stand without crushing, and relief of additional strain due to pillar drawing by the breaking of the roof, are successfully applied in some mining districts in this country. There is nothing in the physical conditions of the Illinois coal fields to indicate that the application of these principles is impossible or even unusually difficult.

IV. METHOD OF INVESTIGATING THE PERCENTAGES OF EXTRACTION

The object of the calculations hereinafter described was the determination of percentages of extraction when plans for the development of a mine are carefully made and all dimensions accurately followed. It was necessary to consider a hypothetical mine or a part of one consistently developed on some predetermined plan. The discussion has been confined to the panel system, because it represents the highest development reached in the extraction of coal by rooms and pillars. It is upon this system that all large modern mines in Illinois are projected.

The term *panel system* originally implied the isolation of a group of rooms, called a panel, from other such groups or panels, by a surrounding pillar of coal pierced on one side only by the room entries. The term is now frequently applied to a system in which the room entries do not terminate in the panel but are driven through to the next cross entry, the block of rooms thus being opened at both ends instead of only at one, the pillars between the ends of panels being omitted.

The present tendency in Illinois seems to be toward the adoption of a more nearly completely isolated panel than has been used though the fire pillars remaining are too narrow to resist squeezing. On this basis the values in the tables and diagrams given have been calculated. The assumed pillars between the ends of adjacent panels are, however, very thin and approximately the same values will be found if these pillars are omitted. The figures and diagrams will apply very closely to either form of the panel system.

11. *Basis of Calculation.*—In the following discussion extraction is calculated on the basis of area excavated instead of on that of tonnage produced. When the workings are of uniform height throughout the mine, the extraction on the basis of tonnage is proportional to that on the basis of area, but, if a portion of the coal is left at top or bottom as is frequently the case in thick coal and under a poor roof, the ratio of tonnage to area may vary in different parts of the mine. Whenever coal is left on the top or bottom, the extraction on a tonnage basis is less than that on an area basis. To get the per-

centage of extraction on a tonnage basis from that on an area basis, the latter should be multiplied by the ratio of thickness mined to the total thickness of the bed. In some parts of Illinois, for example, where the thickness of the coal is nine feet or more, only about seven feet of the coal is extracted. In such places the tonnage produced cannot be more than seven-ninths, or 78 per cent, of that indicated by the area excavated and is less if the thickness of the coal is greater than nine feet. This fact should be borne in mind in considering the percentages of extraction given in this bulletin. In other words these percentages are the maximum amounts of coal which it is possible to get with the given dimensions of workings without the gouging of pillars or the extraction of pillar coal on the retreat. As there is always some waste in mining, the extractions obtained in practice with similar dimensions may be expected to fall below those indicated in the tables. The amount of waste is variable, but it is doubtful if it is ever less than 5 per cent.

12. *Method of Computation.*—An area of 160 acres was selected as large enough to give sufficiently accurate results, and workings were laid out for this area. Since an area of nearly an acre is worked out per day in the larger mines, which produce 4000 tons, or more, per day as now operated in Illinois, it will be seen that 160 acres is only a small part of the tract developed by a single large mine; in fact it represents only about 160 days' work. Accordingly in planning the projection, no attempt was made to lay out 160 acres as a complete mine, but this small tract was assumed to be part of a larger district and was treated as if a square of 160 acres had been taken from the map of a large mine.

If the 160 acres had been developed by itself, one would naturally assume that the main entry was driven through the middle of the tract and that the cross entries were driven equal distances to each side. Instead of this assumption it was determined as a matter of simplification that the line of the ends of a series of panels driven from one cross entry should constitute one border, *m - n*, and the sides of a series of panels should constitute another border, *n - o* (Fig. 1).

In this 160-acre tract workings were laid out with different dimensions and the percentages of extraction for these different dimensions calculated. The room lengths chosen were 200 feet, 250 feet, and 300 feet. The numbers of rooms per entry chosen were 8, 12, 16,

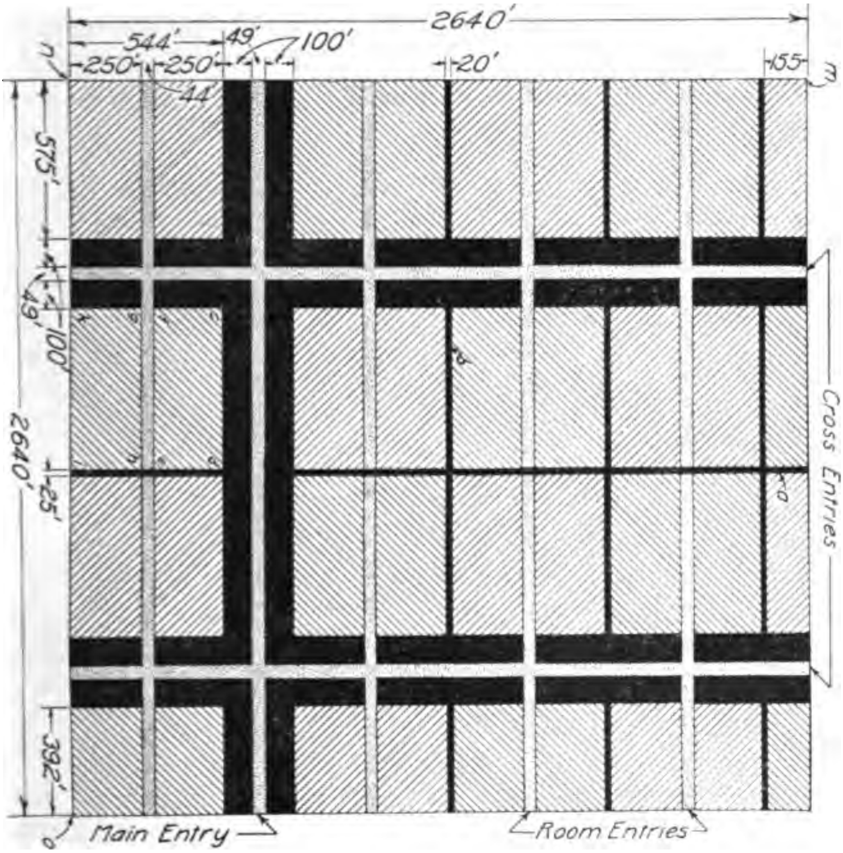

FIG. 1. MAP OF 160-ACRE TRACT SELECTED FOR INVESTIGATION

20, 24, and 28. The cases assumed include, of course, only a few of the many dimensions and numbers of rooms that may occur, but they show the effects of variation in dimensions and number.

For the first calculation it was assumed that all rooms should be 25 feet wide and driven on 50-foot centers. After the method had been developed for these dimensions, calculations were made for different room widths, namely, 20, 30, 35, and 40 feet. Other assumptions made with regard to various portions of the workings will be explained in the detailed consideration of the calculations of area and extraction.

No allowance was made for a barrier pillar around the tract since the barrier pillar left around the borders of a mine constitutes only a very small percentage of the total area, and the proportion which would be chargeable to an area of 160 acres would be insignificant.

One result of the limitation of the area is the occurrence of certain irregularities in the percentages of area occupied by different portions of the workings and in the percentages of extraction. These irregularities would not be found if a larger tract were under consideration. They will be explained in the discussion of the diagrams showing areas and percentages of extraction (Figs. 4 to 9).

The dimensions assumed are as follows:

	Feet
Entry width	12
Main entry pillar	25
Cross entry pillar	25
Room entry pillar	20
Entry cross-cut width	12
Entry cross-cut centers	72
Barrier pillars	100
Pillars at sides of panels	20
Pillars at ends of panels	25
Room neck, width	18
Room neck, length	12
Distance from entry rib to point where room reaches full width	18
Room cross-cut width	18

The constant quantities in the calculations are the dimensions of the tract under consideration, the widths of entries and entry pillars, the spacing and width of entry cross-cuts and room cross-cuts, the dimensions of room necks, and the widths of barrier pillars and of pillars at sides and ends of panels. The variables are the length of rooms, the width of rooms, and the number of rooms per panel. Changes in these variables involve changes in the percentages of area occupied by different portions of the workings and in the percentage of extraction in the portions occupied by rooms and pillars.

13. *Method of Procedure.*—The method of procedure involved: first, the determination of the percentage of coal won or lost in any portion of the workings, such as rooms and pillars, and barriers, and secondly, the determination of the percentage of the entire area

occupied by this portion. A calculation was made, for example, of the percentage of extraction inside a panel and then of the percentage of the total area occupied by panels. A summation of the extractions in different workings gave the total extraction.

Three classes of workings are considered: (1) rooms and pillars, (2) entries, and (3) pillars outside the panels. These divisions are taken up separately and in order.

In determining the area excavated in the room and pillar area of the panel, that is, the area of the panel mined out with the exception of the room entry, *cdef* and *ghik*, Fig. 1, a calculation of the area of a single room and its cross-cuts was made. This area was multiplied by the number of rooms per panel, proper allowance being made for the fact that there is always one more room than pillars on an entry and that the total area of cross-cuts is calculated from the number of pillars. To calculate the area taken out per room the area lost at the neck was subtracted from the product of the width and the length of the room.

The forms and the dimensions of the room necks and cross-cuts are shown in Fig. 2. The area lost at the room neck in the case of a room 25 feet wide is

$$2 \times 3.5 \times \frac{18+12}{2} = 105 \text{ square feet}$$

In all cases it was assumed that cross-cuts were staggered and that the number of cross-cuts through any pillar was either one more or one less than that made through the adjoining pillars. Cross-cuts were so spaced that no working place would be driven more than 60 feet ahead of the air current. This arrangement gives an average of 1½ cross-cuts per pillar for the 200-foot rooms, and 2½ for the 250-foot rooms. This method of arranging cross-cuts is common but not universal. The percentage of area occupied by cross-cuts is small, however, and it makes little difference, so far as the percentage of extraction is concerned, whether the cross-cuts are assumed to be in a straight line or staggered. The area of cross-cuts per pillar in the case of the 250-foot room is

$$2.5 \times 18 \times 25 = 1{,}125 \text{ square feet}$$

The area of the rooms turned from one entry, with their cross-cuts, assuming 12 rooms per entry and a room length of 250 feet, is

$$12\,[(25 \times 250) - 105] + (11 \times 2.5 \times 18 \times 25) = 86{,}115 \text{ square feet}$$

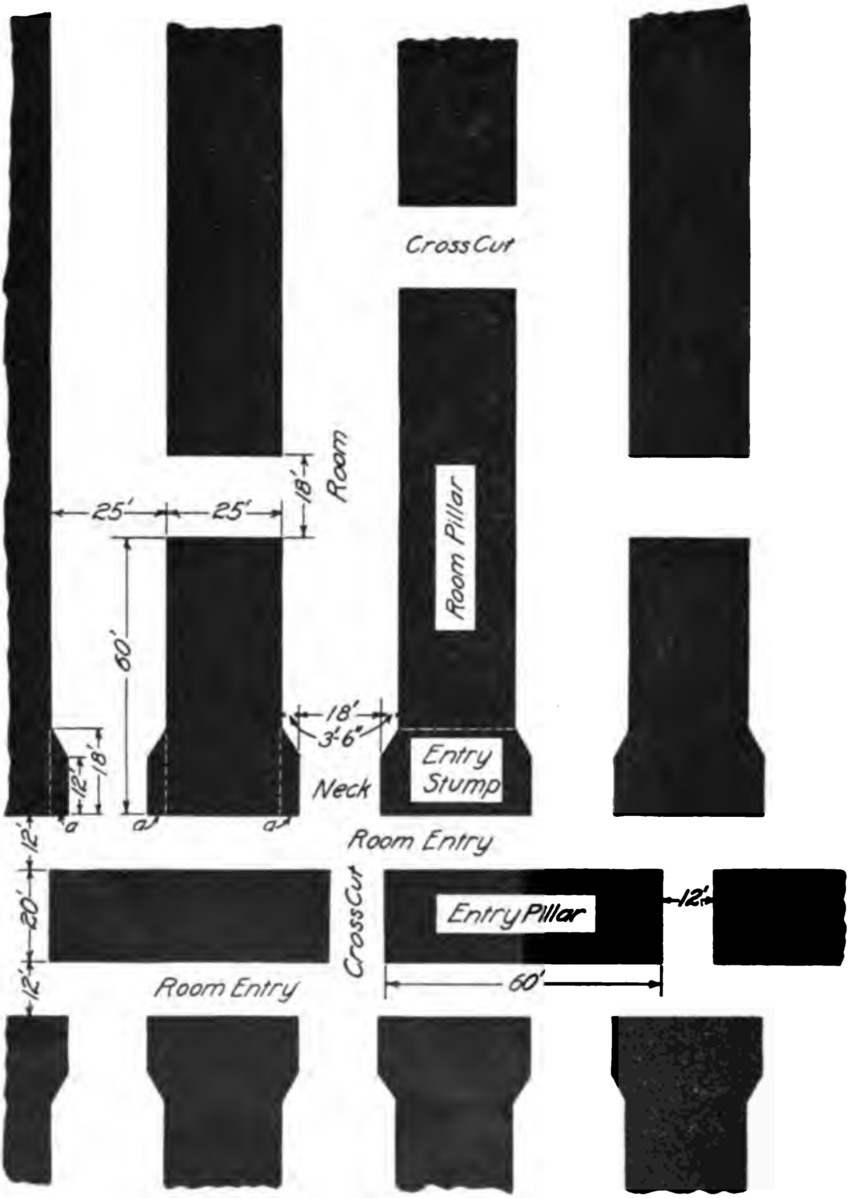

FIG. 2. ROOM ENTRY AND ROOM NECKS

In the following computations it is assumed that rooms are turned from both the room entries, and the area of the number of rooms and room cross-cuts in the panel is

$$2 \times 86{,}115 = 172{,}230 \text{ square feet}$$

The area devoted to rooms and pillars in a panel of 12 rooms, 25 feet wide on 50-foot centers and 250 feet long, is

$$[24 \times 25 \times 250] + [22 \times 25 \times 250] = 287{,}500 \text{ square feet}$$

and the percentage of extraction is

$$\frac{172{,}230 \times 100}{287{,}500} = 59.91 \text{ per cent}$$

14. *Lengths of Entries.*—The lengths of entries are obtained by measurement or by calculation. The length given in each case is that of the double entry, e. g., the length of the main entry is 2640 feet.

15. *Percentage of Extraction in Entries.*—With the following notation,

Le = length of entry
We = width of entry
n = number of entries (2 for double entry, 3 for triple entry)
Wp = width of entry pillar
Wc = width of cross-cuts
Cc = cross-cut centers

the percentage of extraction in any entry or group of entries is expressed by the formula:

$$\frac{[(n \times Le \times We) + (n-1)\ (\frac{Le}{Cc} \times Wc \times Wp)] \times 100}{(n \times Le \times We) + (n-1) \times Le \times Wp}$$

With the dimensions assumed on page 18, the percentage of extraction in room entries is

$$\frac{[(2 \times 12) + (\frac{12}{72} \times 20)] \times 100}{44} = 62.12 \text{ per cent}$$

In the same way the percentage of extraction in main entry and cross entries is

$$\frac{[(2\times12)+(\frac{12}{72}\times25)]\times100}{49}=57.48 \text{ per cent}$$

The difference in extraction between the main and cross entries and the room entries is due to the differences in width of entry pillars.

The area extracted in the room entries inside the panel is equal to the area occupied by the entries and entry pillar multiplied by the percentage of extraction:

$$44\times575\times0.6212=15{,}716 \text{ square feet}$$

16. *Percentage of Extraction Inside the Panel.*—The total area extracted inside the panel is the sum of the areas of rooms with their cross-cuts and of the entries and their cross-cuts.

$$172{,}230+15{,}716=187{,}946 \text{ square feet}$$

and the percentage of extraction is

$$\frac{187{,}946\times100}{544\times575}=60.09 \text{ per cent}$$

in which 544 is the width of the panel and 575 the length.

17. *Percentage of the Total Area Occupied by Panels.*—In any restricted area, such as that under consideration, there will be in most instances a number of whole panels and parts of others which can be determined by plotting or by computation. In the case under consideration, which is illustrated in Fig. 1, there were 12 whole panels 544 by 575 feet, 3 parts of panels 155 by 575 feet, 1 part 155 by 392 feet, and 4 parts 544 by 392 feet. The total area of the panels was then:

	Square Feet
12×544×575 =	3,753,600
3×155×575 =	267,375
155×392 =	60,760
4×544×392 =	852,992
	4,934,727

The total percentage of area occupied by panels is

$$\frac{4{,}934{,}727 \times 100}{6{,}969{,}600} = 70.80 \text{ per cent}$$

18. *Percentage of Total Area Extracted in All Panels.*—This is the product of the percentage of total area occupied by panels and the percentage of extraction in panels:

$$70.80 \times 0.6009 = 42.54 \text{ per cent}$$

19. *Entry Area Outside the Panels.*—A double main entry is assumed to be driven across the tract, its area being 2,640 × 49 = 129,360 square feet. In the case of the two double cross entries the width is the same, but the length is less by the width of the main entry from which the two cross entries are driven. The area of these two is

$$2 \times 2{,}591 \times 49 = 253{,}918 \text{ square feet}$$

The area devoted to the main entry was the same in all instances since only one main entry was assumed. The area of cross entries varied considerably as there were sometimes three cross entries, sometimes two and sometimes only one.

The area of room entries outside the panel is

$$16 \times 44 \times 100 = 70{,}400 \text{ square feet}$$

In the tract under consideration, illustrated in Fig. 1, there are no fractional widths of cross entry barriers to be considered and all the portions of room entries outside the panels are 100 feet long. In some other cases there were fractions of barrier pillars and therefore different lengths of room entries outside the panels.

The total area occupied by entries outside the panels is the sum of the areas of main entry, cross entries, and room entries with their entry pillars:

	Square Feet
Main entry	129,360
Cross entries	253,918
Room entries	70,400
	453,678

The area of the room entries and entry pillars inside the panels is

$$12 \times 44 \times 575 + 4 \times 44 \times 392 = 372{,}592 \text{ square feet}$$

20. *Percentage of Area Occupied by Entries.*—The percentages of total area occupied by entries are as follows:

Main entry	$\frac{129{,}360 \times 100}{6{,}969{,}600} = 1.86$ per cent
Cross entries	$\frac{253{,}918 \times 100}{6{,}969{,}600} = 3.64$ per cent
Room entries—outside panels	$\frac{70{,}400 \times 100}{6{,}969{,}600} = 1.01$ per cent
Room entries—inside panels	$\frac{372{,}592 \times 100}{6{,}969{,}600} = 5.35$ per cent

The percentage of the total area occupied by room entries both outside and inside the panel is

$$1.01 + 5.35 = 6.36 \text{ per cent}$$

21. *Percentage of Total Area Extracted in Entries.*—To get the percentage of total area extracted in entries, the percentage of area occupied by the entry is multiplied by the calculated percentage of extraction, as follows:

	Percentage
Percentage of total area extracted in room entries inside panels	$5.35 \times 0.6212 = 3.32$
Percentage of total area extracted in room entries outside panels	$1.01 \times 0.6212 = 0.63$
Percentage of total area extracted in cross entries	$3.64 \times 0.5748 = 2.09$
Percentage of total area extracted in main entry	$1.86 \times 0.5748 = 1.07$
Total percentage extracted in entries	7.11

22. *Summary of Percentages of Extraction.*—The extraction in the different parts of the mine may then be summarized as follows:

	Percentage
Panels	42.54
Room entries—outside panels	0.63
Cross entries	2.09
Main entry	1.07
Total	46.33

23. *Area Left in Pillars Outside the Panels.*—The only area remaining to be considered is that occupied by barrier pillars and pillars at sides and ends of panels. As it is assumed that this pillar coal is entirely lost the only thing to be considered is the area and the percentage of total area occupied by the pillars. If in any case it is to be assumed that some of this coal is to be saved, the amount thus extracted may be found by multiplying the area of the pillars by the percentage of extraction.

It is, of course, not always true that all the coal thus left is lost, and theoretically this is seldom the case, as it is generally intended that a large part of the coal left, especially in barrier pillars, will be extracted later. In some coal mining districts this coal is extracted, but in the Illinois fields very little of the barrier coal is mined; consequently it seems better to assume complete loss of this coal rather than an arbitrary percentage of recovery.

In the case of each entry barrier the area is the length of the barrier multiplied by its width, minus the area of the entries which extend through it but including the entry pillar. The area of the main entry barrier pillars, as thus defined, is

$$2\times100\times2640-[(8\times100\times12)+(4\times25\times12)]=517{,}200 \text{ square feet}$$

The percentage of the total area devoted to main entry barrier pillars is

$$\frac{517{,}200\times100}{6{,}969{,}600}=7.42 \text{ per cent}$$

This percentage is unusually high because of the small area considered. In the case of a square area of 5,000 acres with one main entry with barrier pillars 100 feet wide, the percentage of area occupied by the main entry barriers is about 1.3 per cent.

The length of the cross entry barrier pillars is the distance across the tract minus the width of the main entry with its two barrier pillars. The area is

$$4\times100(2640-249)-[(32\times100\times12)+(16\times20\times12)]=914{,}160 \text{ square feet}$$

The percentage of total area is

$$\frac{914{,}160\times100}{6{,}969{,}600}=13.12 \text{ per cent}$$

The area left in pillars at the ends of panels is, in the cases assumed

$$25\times(2640-249) = 59{,}775 \text{ square feet}$$

The percentage of the total area occupied by these pillars is

$$\frac{59{,}775\times100}{6{,}969{,}600}=0.86 \text{ per cent}$$

The area of the pillars left at the sides of panels is, in the case assumed

$$(9\times20\times575)+(3\times20\times392) = 127{,}020 \text{ square feet}$$

The percentage of total area occupied is

$$\frac{127{,}020\times100}{6{,}969{,}600}=1.82 \text{ per cent}$$

The sum of the various items of loss in pillars outside the panels and entries is

Main entry barrier	7.42
Cross entry barrier	13.12
Total in entry barriers	20.54
In pillars at ends of panels	0.86
In pillars at sides of panels	1.82
Total left in pillars outside the panels	23.22

24. *Percentages of Extraction with Different Room Widths.*—In computing the percentage of total extraction with various other room widths considered: viz., 20, 30, 35, and 40 feet the dimensions of room centers were kept unchanged at 50 feet. It is recognized that this would not be the practice, but a change of room centers would have so complicated the problem as to require a much longer period for the attainment of results. The method of calculation has been clearly indicated and it is possible, by selecting room and pillar widths of the proper ratio in Tables 4, 5, and 6 to obtain close approximations to the percentages of extraction and loss with any widths of room and pillar desired.

It was assumed that the length of the panels and the percentage of total area devoted to panels for each number of rooms per entry were not changed by these alterations in room and pillar dimensions. This assumption is not strictly true, since the length of the panel varies with the room width; for example, a panel of eight 40-foot rooms to the entry is 390 feet long instead of the 375 feet assumed. The discrepancies are greatest in the instances of widest rooms, because the difference between real panel length and assumed panel length is greatest. There are two errors which partially neutralize each other, and it was found by computation for the extreme cases that the final errors were very small. In the first place if the panel is actually longer than is assumed, the percentage of extraction in the panel is less than that computed. In the second place if the panel is longer than assumed, the total area occupied by panels is greater than that computed. The errors for the first and the last figures in the various columns of Table 4 are as follows: In the column for 20-foot rooms the first figure is 0.05 too high and the last figure is 0.29 too low; in the column for 25-foot rooms the figures are correct; in the column for 30-foot rooms the first figure is 0.05 too low and the last figure 0.04 too high; in the column for 35-foot rooms the first figure is 0.11 too low and the last figure 0.25 too high; in the column for 40-foot rooms the first figure is 0.15 too low and the last figure 0.67 too high. The other figures in each column have errors intermediate between those of the first and last figures. The errors all being less than one per cent, it is apparent that this method of calculation is sufficiently accurate for all purposes for which it is likely to be used, as departures from the projected method of working will account for greater differences between the actual and the computed output than the small errors in the tables.

25. *Tables and Diagrams.*—For convenience in reference the values obtained by the methods described in the preceding pages have been collected in Tables 1-7, which give the percentages of total area occupied by different classes of workings, the percentages of extraction in these different classes, the percentages of total area excavated in the different classes of workings, the percentage of total area won, the lengths of entries and the amounts of narrow work.

Most of the facts given in the tables are shown graphically in Figs. 3 to 9. These figures permit comparison between the results obtained by the use of different dimensions of workings.

For 25-foot rooms, Table 1 shows in column 3 the percentage of

TABLE 1

EXTRACTION IN PANELS

25-FOOT ROOMS

Length of Rooms (Feet)	Number of Rooms per Room Entry	Percentage of Extraction in Room and Pillar Area[1]	Percentage of Extraction inside the Panel	Percentage of Total Area Occupied by Panels	Percentage of Total Area Extracted in Panels
200	8	58.51	58.87	62.17	36.60
	12	57.54	57.99	70.20	40.71
	16	57.06	57.56	77.09	44.37
	20	56.78	57.31	78.45	44.96
	24	56.60	57.15	78.45	44.83
	28	56.47	57.03	79.28	45.21
250	8	60.89	60.92	62.71	38.20
	12	59.91	60.09	70.80	42.54
	16	59.45	59.67	77.76	46.40
	20	59.19	59.43	79.14	47.03
	24	59.01	59.27	79.13	46.90
	28	58.89	59.15	79.97	47.30
300	8	62.39	62.37	63.25	39.45
	12	61.49	61.53	71.41	43.94
	16	61.05	61.12	78.43	47.94
	20	60.80	60.88	79.81	48.59
	24	60.63	60.73	79.81	48.47
	28	60.51	60.62	80.65	48.89

[1] Room and pillar area shown by hatching in Fig. 1.

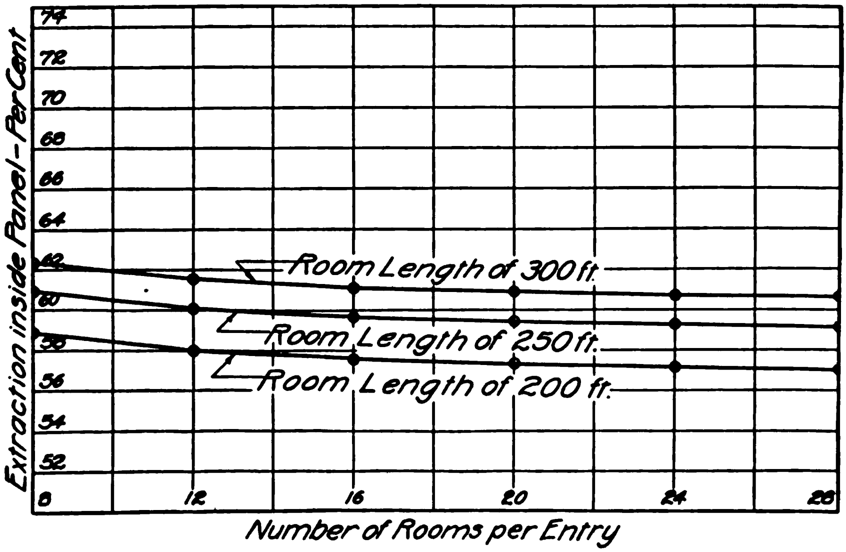

FIG. 3. PERCENTAGE OF EXTRACTION INSIDE THE PANEL FOR ROOMS 250 FEET LONG, 25 FEET WIDE, ON 50-FOOT CENTERS

extraction in the room and pillar area obtained with each length of room and each number of rooms per entry; in column 4 the total percentage of extraction inside the panel, that is, the sum of the extraction in rooms and room cross-cuts, and in room entries; in column 5 the percentage of the total area included in panels; and in column 6 the percentage of the total area extracted in panels. The percentage extracted in the panels plus the percentage extracted in the entries outside the panels gives the total percentage of extraction.

The values in column 4 of Table 1, the percentage of extraction inside the panel for rooms 25 feet wide, are illustrated by Fig. 3. For a given width of room and pillar the percentage of extraction inside the panel decreases somewhat as the number of rooms per entry increases, because the proportion of the total panel area remaining in pillars increases as the number of rooms increases and the percentage of extraction correspondingly decreases. With only two rooms and one pillar approximately 1/3 of the coal is left in the pillar, while with the 10 rooms and 9 pillars $^{9}/_{19}$ remain and with 20 rooms and 19 pillars $^{19}/_{39}$ remain.

The values in column 5 of Table 1 are illustrated in Fig. 4 which shows the percentage of total area included in panels for 25-foot rooms, 200 feet, 250 feet, and 300 feet long respectively, and for 8, 12, 16, 20, 24, and 28 rooms per entry. These diagrams show that the percentage of area devoted to panels increases with the length of the room and the number of rooms per entry. The increase is especially rapid for the smaller number of rooms per entry and comparatively small for the larger number of rooms per entry.

It will be noticed that there is a reversal in the direction of the lines at 24 rooms per entry shown in the broken lines based on the figures in the table, and that there is no corresponding change in direction of the diagrams for percentage of extraction inside the panel. These facts show that the drop in the diagrams of total extraction (Fig. 6) at 24 rooms per entry is due to the irregularity of the increase of percentage of total area included in panels, which in turn is due to the limited area considered. The solid lines (Figs. 4 and 6) show the positions when a large area is considered, and the same results are reached by calculation for 25 rooms per entry.

It will also be noticed that there is a comparatively rapid change in the direction of the lines when there are about 16 rooms per panel. This fact indicates that with 16 rooms per panel, or less, the percent-

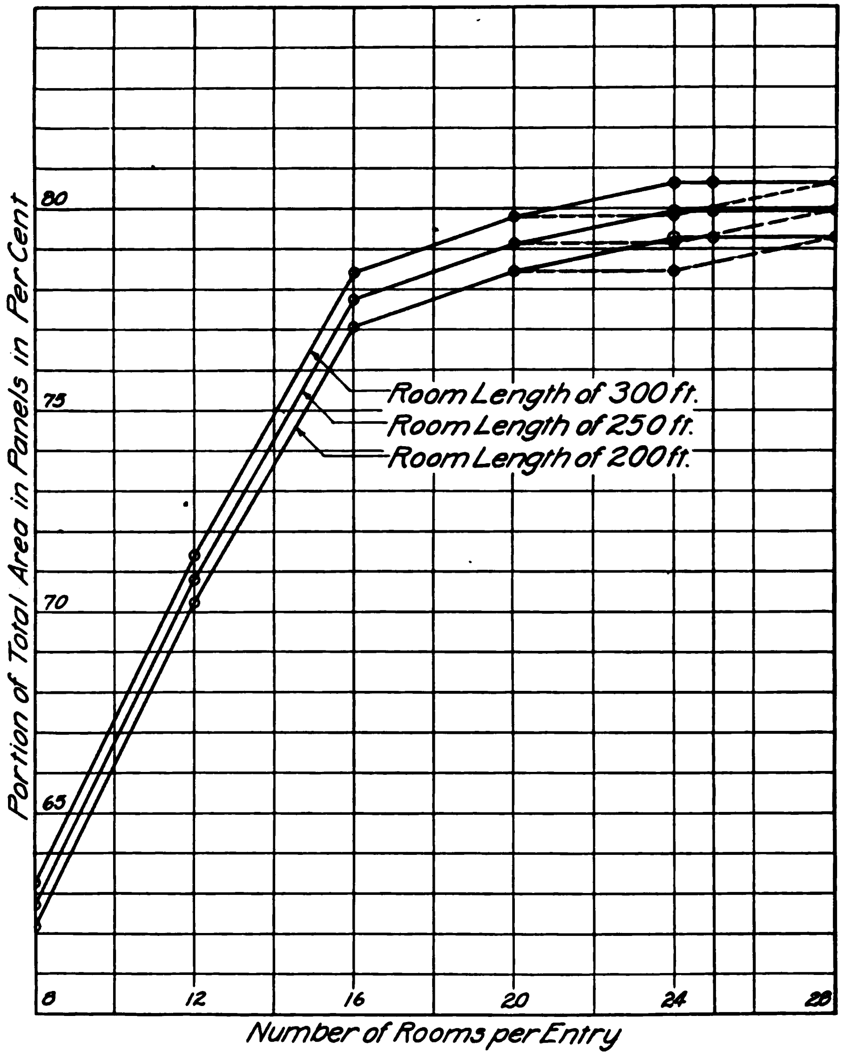

FIG. 4. PERCENTAGE OF TOTAL AREA INCLUDED IN PANELS FOR ROOMS 25 FEET WIDE, ON 50-FOOT CENTERS

age of area occupied by panels increases rapidly with the number of rooms per entry. For 16 rooms, or more, the increase is slow. This change also shows as does the diagram for total percentage of extraction, that this percentage increases comparatively rapidly with the increase of number of rooms per entry to about 16 and that after this number is reached the rate of increase is small.

TABLE 2

EXTRACTION IN ENTRIES

Length of Rooms (Feet)	Number of Rooms per Room Entry	Percentage of Total Area Occupied by Entries					Percentage of Total Area Extracted in Entries			
		Main Entry	Cross Entry	Room Entry		Total	Main Entry	Cross Entry	Room Entry	Total
				Outside Panel	Inside Panel					
200	8	1.86	5.46	1.79	5.92	15.03	1.07	3.14	4.79	9.00
	12	1.86	3.64	1.26	6.68	13.44	1.07	2.09	4.93	8.09
	16	1.86	1.82	0.76	7.34	11.78	1.07	1.05	5.03	7.15
	20	1.86	1.82	0.63	7.47	11.78	1.07	1.05	5.03	7.15
	24	1.86	1.82	0.63	7.47	11.78	1.07	1.05	5.03	7.15
	28	1.86	1.82	0.63	7.55	11.86	1.07	1.05	5.08	7.20
250	8	1.86	5.46	1.43	4.74	13.49	1.07	3.14	3.83	8.04
	12	1.86	3.64	1.01	5.35	11.86	1.07	2.09	3.95	7.11
	16	1.86	1.82	0.61	5.87	10.16	1.07	1.05	4.02	6.14
	20	1.86	1.82	0.51	5.97	10.16	1.07	1.05	4.03	6.15
	24	1.86	1.82	0.51	5.97	10.16	1.07	1.05	4.03	6.15
	28	1.86	1.82	0.51	6.04	10.23	1.07	1.05	4.07	6.19
300	8	1.86	5.46	1.43	4.74	13.49	1.07	3.14	3.83	8.04
	12	1.86	3.64	1.01	5.35	11.86	1.07	2.09	3.95	7.11
	16	1.86	1.82	0.61	5.87	10.16	1.07	1.05	4.02	6.14
	20	1.86	1.82	0.51	5.97	10.16	1.07	1.05	4.03	6.15
	24	1.86	1.82	0.51	5.97	10.16	1.07	1.05	4.03	6.15
	28	1.86	1.82	0.51	6.04	10.23	1.07	1.05	4.07	6.19

Table 2 gives the percentage of total area occupied by entries and the percentage of total area extracted in entries, all for rooms 25 feet wide. Column 3 gives the percentage of total area in the main entry, column 4 the percentage of total area in the cross entries, column 5 the percentage of total area in the room entries outside the panel, column 6 the percentage of total area in the room entries inside the panel, and column 7 the total percentage of area occupied by entries. Column 8 gives the percentage of total area extracted in main entry, column 9 the percentage extracted in cross entries, column 10 the percentage extracted in room entries, and column 11 the total percentage of area extracted in entries.

The values in Table 2 are illustrated by Fig. 5 which shows the percentage of total area occupied by entries, including the entry pillars, for different numbers of rooms per entry and different lengths of rooms. The diagrams are drawn for 25-foot rooms, but, as shown in the discussion of the methods of calculation, they would be only slightly changed if different room widths were considered.

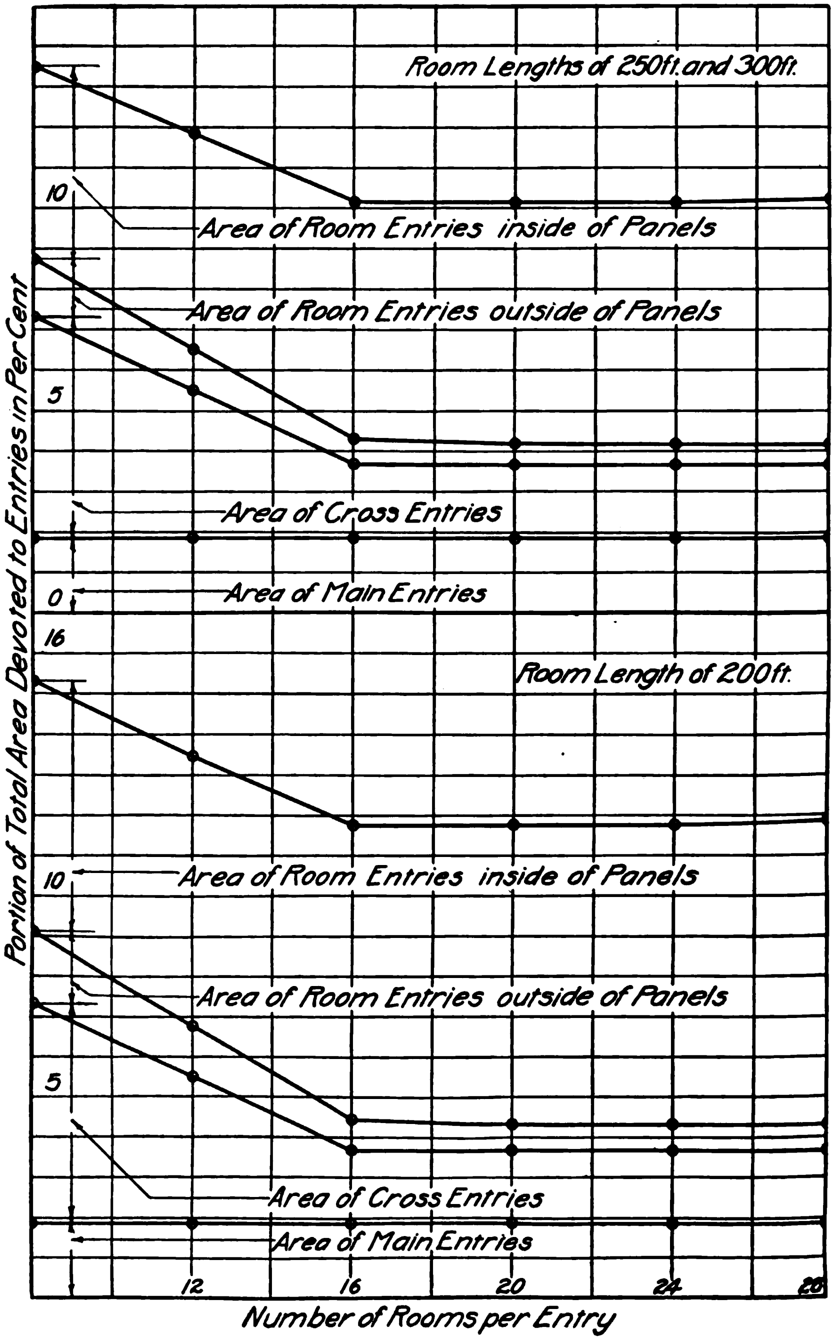

FIG. 5. PERCENTAGE OF TOTAL AREA OCCUPIED BY ENTRIES FOR ROOMS 25 FEET WIDE, ON 50-FOOT CENTERS

Column 3 of Table 3 shows the amounts of narrow work in entries. Columns 4, 5, 6, and 7 give respectively the length of main entries, cross entries, room entries and total entries, in all cases without entry cross-cuts. It should be noted that these are the lengths of double entries and not of single entries; for example, the length of the main entry, 2640 feet, is the distance across the tract.

TABLE 3

LENGTH OF ENTRIES AND YARDS OF NARROW WORK

Length of Rooms (Feet)	Number of Rooms per Room Entry	Yards of Narrow Work	Length of Double Entries in Feet[1]			
			Main Entry	Cross Entry	Room Entry	Total
200	8	17192	2640	7773	12215	22628
	12	15488	2640	5182	12585	20407
	16	13707	2640	2591	12830	18061
	20	13707	2640	2591	12830	18061
	24	13707	2640	2591	12830	18061
	28	13804	2640	2591	12955	18186
250	8	15333	2640	7773	9772	20185
	12	13591	2640	5182	10068	17889
	16	11752	2640	2591	10264	15495
	20	11771	2640	2591	10264	15495
	24	11771	2640	2591	10264	15495
	28	11848	2640	2591	10364	15595
300	8	15333	2640	7773	9772	20185
	12	13591	2640	5182	10068	17889
	16	11752	2640	2591	10264	15495
	20	11771	2640	2591	10264	15495
	24	11771	2640	2591	10264	15495
	28	11848	2640	2591	10364	15595

The total cross entry length does not vary with the length of rooms, but decreases with the increase in the number of rooms per entry. This decrease is actually more regular than is indicated, because the table is for a small tract in which a cross entry is occasionally forced outside the boundary by increase of number of rooms per entry.

In the tract considered the total room entry length is the same for 250-foot and 300-foot rooms, but is greater for 200-foot rooms. If a large area were considered, the lengths for the 250-foot and 300-foot rooms would not coincide, but the length for the 250-foot rooms would lie between those of the 200-foot and 300-foot rooms. The total length of room entries increases slightly as the number of rooms per entry increases.

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[1] These lengths refer to pairs of entries, not to single entries: i. e., they represent haulage distances along the entries. The total length of narrow work for which yardage is paid is therefore double the length given, plus the sum of the lengths of cross-cuts.

TABLE 4

PERCENTAGE OF EXTRACTION IN PANELS, IN ENTRIES, AND TOTAL EXTRACTION[1]

Length of Rooms (Feet)	Number of Rooms per Room Entry	Percentage of Extraction Inside Each Panel					Percentage of Total Area Extracted in All Panels					Percentage of Total Area Extracted in Entries Outside Panels	Total Percentage Extracted				
		20-ft. Rooms	25-ft. Rooms	30-ft. Rooms	35-ft. Rooms	40-ft. Rooms	20-ft. Rooms	25-ft. Rooms	30-ft. Rooms	35-ft. Rooms	40-ft. Rooms		20-ft. Rooms	25-ft. Rooms	30-ft. Rooms	35-ft. Rooms	40-ft. Rooms
200	8	51.12	58.87	66.62	74.38	82.13	31.78	36.60	41.42	46.24	51.06	5.32	37.10	41.92	46.74	51.56	56.38
	12	50.46	57.99	65.52	73.05	80.59	35.42	40.71	46.00	51.28	56.57	3.94	39.36	44.65	49.94	55.22	60.51
	16	50.14	57.56	64.99	72.41	79.84	38.65	44.37	50.10	55.82	61.55	2.59	41.24	46.96	52.69	58.41	64.14
	20	49.95	57.31	64.67	72.04	79.40	39.19	44.96	50.73	56.51	62.29	2.51	41.70	47.47	53.24	59.02	64.80
	24	49.82	57.15	64.47	71.79	79.10	39.08	44.83	50.58	56.32	62.05	2.51	41.59	47.34	53.09	58.83	64.56
	28	49.74	57.03	64.32	71.61	78.91	39.43	45.21	50.99	56.77	62.56	2.51	41.94	47.72	53.50	59.28	65.07
250	8	53.25	60.92	68.59	76.26	83.93	33.39	38.20	43.01	47.82	52.63	5.10	38.69	43.30	48.11	52.92	57.73
	12	52.65	60.09	67.52	74.92	82.39	37.27	42.54	47.80	53.04	58.33	3.79	41.06	46.33	51.59	56.83	62.12
	16	52.35	59.67	66.99	74.01	81.62	40.70	46.40	52.09	57.55	63.47	2.50	43.20	48.90	54.59	60.15	65.97
	20	52.18	59.43	66.67	73.93	81.17	41.30	47.03	52.76	58.51	64.24	2.44	43.74	49.47	55.20	60.95	66.68
	24	52.05	59.27	66.47	73.67	80.86	41.19	46.90	52.60	58.30	63.98	2.44	43.63	49.34	55.04	60.74	66.42
	28	51.98	59.15	66.36	73.50	80.67	41.57	47.30	53.07	58.78	64.51	2.44	44.01	49.74	55.51	61.22	66.95
300	8	54.75	62.37	69.98	77.60	85.21	34.62	39.45	44.26	49.08	53.90	5.08	39.70	44.53	49.34	54.16	58.98
	12	54.17	61.53	68.89	76.26	83.62	38.68	43.94	49.19	54.46	59.71	3.79	42.47	47.73	52.98	58.25	63.50
	16	53.88	61.12	68.37	75.61	82.85	42.26	47.94	53.63	59.30	64.98	2.50	44.76	50.44	56.13	61.80	67.48
	20	53.71	60.88	68.06	75.23	82.40	42.87	48.59	54.32	60.04	65.76	2.44	45.31	51.03	56.76	62.48	68.20
	24	53.60	60.73	67.85	74.98	82.10	42.78	48.47	54.15	59.84	65.52	2.44	45.22	50.91	56.59	62.28	67.96
	28	53.52	60.62	67.71	74.80	81.89	43.16	48.89	54.61	60.33	66.04	2.44	45.60	51.33	57.05	62.77	68.48

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[1] Room centers 50 feet in all cases.

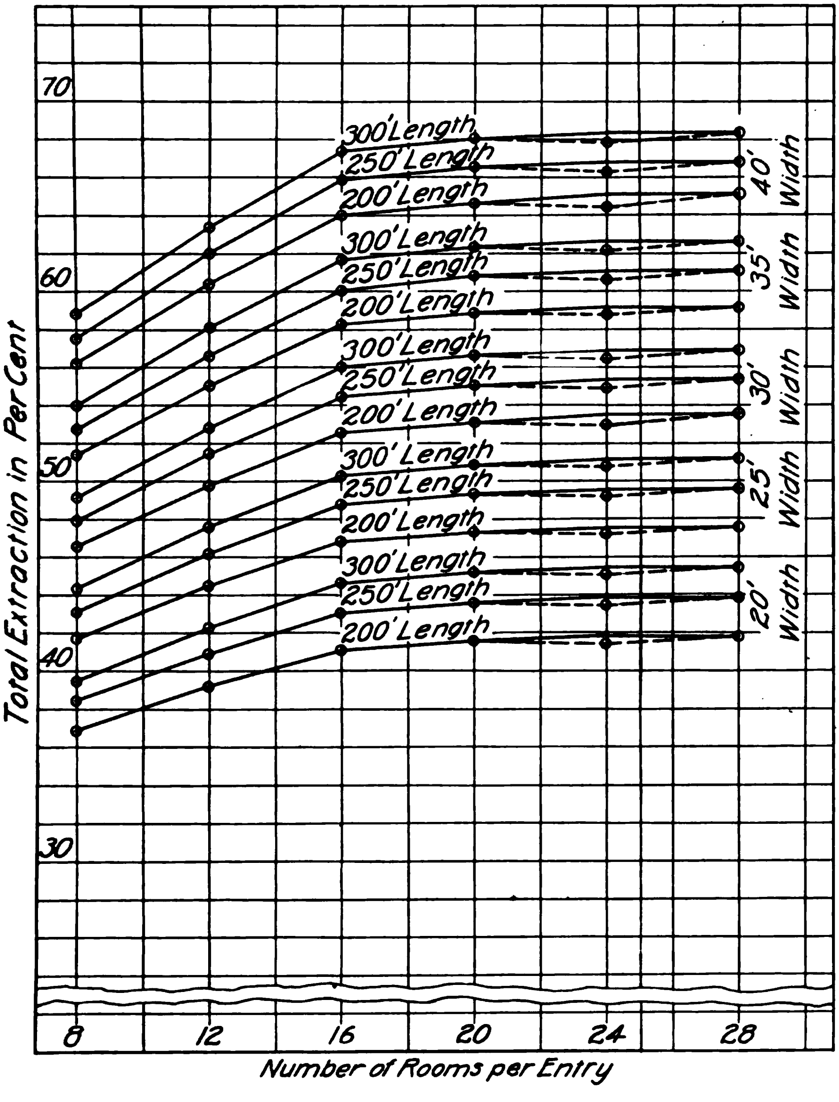

FIG. 6. TOTAL PERCENTAGE OF EXTRACTION

The decrease in length of cross entries with increase of number of rooms per entry ceases at about 16 rooms per entry. If a larger area were considered, the change would be less abrupt than it is.

Table 4 gives the percentages of extraction for all widths of rooms considered. The first group of figures in columns 3, 4, 5, 6, and 7, gives the percentage of extraction inside the panel for each width of room, for each length of room and for each number of rooms per entry. The second group of figures, given in columns 8, 9, 10, 11, and 12, gives the percentage of total area extracted in panels for each width of room, each length of room, and each number of rooms per entry. In each case this percentage is obtained by multiplying the percentage of extraction inside the panel by the percentage of area occupied by panels. The values in column 13 give the percentage of area extracted in entries outside the panels.

The third group of figures, given in columns 14, 15, 16, 17, and 18, gives the total percentage of extraction. This percentage is obtained in each case by adding to the percentage of area extracted in panels the percentage of area extracted in entries outside the panels.

It will be noted that the total percentage of extraction is increased by increasing the length of rooms, the width of the rooms and the number of rooms per entry.

The values for total extraction given in Table 4 are shown graphically by Fig. 6. This set of diagrams shows plainly, in the broken lines plotted from the figures in the table, one of the irregularities resulting from the use of a small area as a basis for calculation: that is, the apparent drop in total percentage of extraction at 24 rooms per entry. The percentage of extraction does not actually drop at this point, however, the apparent drop being due to the consideration of a limited area. Calculations for 25 rooms per entry place the curve at its approximately proper position, and the solid lines show this position.

Table 5 shows the percentage of loss inside the panel and the percentage of total area lost inside the panels, for all conditions considered. Columns 3 to 7 inclusive give the percentages of loss inside the panel for the different conditions; columns 8 to 12 inclusive give the percentage of total area lost inside the panels. These latter figures are obtained by multiplying the percentage of area devoted to panels by the percentage of loss inside the panels, which is obtained by subtracting the percentage of extraction inside the panel from one hundred.

Table 6 gives the percentages of total area left in pillars outside panels; that is, all coal left in the mine except that in room pillars

TABLE 5

PERCENTAGE LOST IN PANELS

Length of Rooms (Feet)	Number of Rooms per Room Entry	Percentage of Loss Inside Panels.					Percentage of Total Area Lost Inside Panels				
		20-ft. Rooms	25-ft. Rooms	30-ft. Rooms	35-ft. Rooms	40-ft. Rooms	20-ft. Rooms	25-ft. Rooms	30-ft. Rooms	35-ft. Rooms	40-ft. Rooms
200	8	48.88	41.13	33.38	25.62	17.87	30.39	25.57	20.75	15.93	11.11
	12	49.54	42.01	34.48	26.95	19.41	34.64	29.49	24.20	18.92	13.63
	16	49.86	42.44	35.01	27.59	20.16	38.44	32.72	26.99	21.27	15.54
	20	50.05	42.69	35.33	27.96	20.60	39.26	33.49	27.72	21.93	16.16
	24	50.18	42.85	35.53	28.21	20.90	39.37	33.62	27.87	22.13	16.40
	28	50.26	42.97	36.17	28.39	21.67	39.85	33.99	28.68	22.51	17.18
250	8	46.75	39.08	31.41	23.74	16.07	29.32	24.51	19.70	14.89	10.08
	12	47.35	39.91	32.48	25.08	17.61	33.52	28.26	23.00	17.76	12.47
	16	47.65	40.33	33.01	25.99	18.38	37.05	31.36	25.67	20.21	14.29
	20	47.82	40.57	33.33	26.07	18.73	37.84	32.11	26.38	20.63	14.82
	24	47.96	40.73	33.53	26.33	19.14	37.94	32.23	26.53	20.83	15.15
	28	48.02	40.85	33.64	26.50	19.33	38.40	32.67	26.90	21.19	15.46
300	8	45.25	37.63	30.02	22.40	14.79	28.62	23.80	18.99	14.17	9.35
	12	45.83	38.47	31.11	23.74	16.38	32.73	27.47	22.22	16.95	11.70
	16	46.12	38.88	31.63	24.39	17.15	36.17	30.49	24.81	19.13	13.45
	20	46.29	39.12	31.94	24.77	17.60	36.94	31.22	25.49	19.77	14.05
	24	46.40	39.27	32.15	25.02	17.90	37.03	31.34	25.66	19.97	14.29
	28	46.48	39.38	32.29	25.20	18.11	37.49	31.76	26.04	20.33	14.61

TABLE 6

PERCENTAGE LOST IN PILLARS OUTSIDE THE PANELS EXCEPT IN ENTRIES

Length of Rooms (Feet)	Number of Rooms per Room Entry	Percentage of Total Area Left in Pillars Outside Panel Except Entry Pillars					
		Main Entry Barriers	Cross Entry Barriers	Total in Entry Barriers	At Ends of Panels	At Sides of Panels	Total
200	8	7.34	18.41	25.75	1.72	2.15	29.62
	12	7.42	12.96	20.38	0.86	2.43	23.67
	16	7.50	7.82	15.32	0.86	2.67	18.85
	20	7.50	6.48	13.98	0.86	2.72	17.56
	24	7.50	6.48	13.98	0.86	2.72	17.56
	28	7.50	6.48	13.98	0.00	2.74	16.72
250	8	7.34	18.63	25.97	1.72	1.61	29.30
	12	7.42	13.12	20.54	0.86	1.82	23.22
	16	7.50	7.92	15.42	0.86	2.00	18.28
	20	7.50	6.56	14.06	0.86	2.04	16.96
	24	7.50	6.56	14.06	0.86	2.04	16.96
	28	7.50	6.56	14.06	0.00	2.06	16.12
300	8	7.34	18.63	25.97	1.72	1.08	28.77
	12	7.42	13.12	20.54	0.86	1.22	22.62
	16	7.50	7.92	15.42	0.86	1.34	17.62
	20	7.50	6.56	14.06	0.86	1.36	16.28
	24	7.50	6.56	14.06	0.86	1.36	16.28
	28	7.50	6.56	14.06	0.00	1.37	15.43

and entry pillars. Column 3 gives the percentage of total area occupied by the main entry barriers; column 4 the percentage of total area occupied by cross entry barriers; and column 5 the percentage of total area in all entry barriers, the sum of the two preceding columns. Column 6 gives the percentage of total area left in pillars at ends of panels, column 7 the percentage of total area left in pillars at sides of panels, and column 8 the percentage of total area left in pillars outside the panels except in entries. Column 8 represents the sum obtained by adding together the proper figures in columns 3, 4, 6, and 7.

TABLE 7

EXTRACTION IN WIDE WORK AND IN NARROW WORK

Length of Rooms (Feet)	Number of Rooms per Room Entry	Percentage of Total Extraction Obtained from Narrow Work					Percentage of Total Extraction Obtained from Wide Work				
		20-ft. Rooms	25-ft. Rooms	30-ft. Rooms	35-ft. Rooms	40-ft. Rooms	20-ft. Rooms	25-ft. Rooms	30-ft. Rooms	35-ft. Rooms	40-ft. Rooms
200	8	24.26	21.47	19.26	17.46	15.96	75.74	78.53	80.74	82.54	84.04
	12	20.55	18.12	16.20	14.65	13.37	79.45	81.88	83.80	85.35	86.63
	16	17.34	15.23	13.57	12.24	11.15	82.66	84.77	86.43	87.76	88.85
	20	17.15	15.06	13.43	12.11	11.03	82.85	84.94	86.57	87.89	88.97
	24	17.19	15.10	13.47	12.15	11.07	82.81	84.90	86.53	87.85	88.93
	28	17.17	15.09	13.46	12.15	11.07	82.83	84.91	86.54	87.85	88.93
250	8	20.78	18.57	16.71	15.19	13.93	79.22	81.43	83.29	84.81	86.07
	12	17.32	15.35	13.78	12.51	11.45	82.68	84.65	86.22	87.49	88.55
	16	14.21	12.56	11.19	10.21	9.31	85.79	87.44	88.81	89.79	90.69
	20	14.06	12.43	11.14	10.09	9.22	85.94	87.57	88.86	89.91	90.78
	24	14.10	12.47	11.17	10.13	9.26	85.90	87.53	88.83	89.87	90.74
	28	14.07	12.45	11.15	10.11	9.25	85.93	87.55	88.85	89.89	90.75
300	8	20.25	18.06	16.30	14.85	13.63	79.75	81.94	83.70	85.15	86.37
	12	16.74	14.90	13.42	12.21	11.20	83.26	85.10	86.58	87.79	88.80
	16	13.72	12.17	10.94	9.94	9.10	86.28	87.83	89.06	90.06	90.90
	20	13.57	12.05	10.84	9.84	9.02	86.43	87.95	89.16	90.16	90.98
	24	13.60	12.08	10.87	9.87	9.05	86.40	87.92	89.13	90.13	90.95
	28	13.57	12.06	10.85	9.86	9.04	86.43	87.94	89.15	90.14	90.96

Table 7 gives a comparison between the total extraction made in narrow work and that made in wide work. Columns 3 to 7, inclusive, give the percentage of total extraction obtained from narrow work; that is, from entries and entry cross-cuts for all conditions considered. In each case the total extraction, whatever the actual figure, is considered 100 per cent. Columns 8 to 12, inclusive, give the percentage of total extraction obtained from wide work; that is, from rooms, room necks, and room cross-cuts. When these values are considered, it should be remembered that the limit between wide work and narrow work has been set arbitrarily. It is considered for the purpose of these calculations that all workings less than 18 feet in width are narrow work and all workings 18 feet or more in width are wide work. It is to be noted that the percentage of the total extraction obtained from narrow work decreases as the length of rooms increases, as the number of rooms per entry increases, and as the width of rooms in relation to width of room pillars increases.

As narrow work is more expensive than wide work, efforts will be made to reduce it to the minimum in places where the conditions of roof and floor permit. This reduction can sometimes be accomplished by increasing the width of entries and entry cross-cuts. Where this increase is impossible, the only means of reducing the amount of narrow work is by decreasing the length of entries, assuming that room cross-cuts and room necks are wide work. This assumption, however, is not always true. The work of J. C. Quade (see Appendix I) illustrates the reduction of narrow work by increase of the width of room cross-cuts.

Summaries of the percentages won and lost in different portions of the workings are given in Figs. 7, 8, and 9, which illustrate the results with rooms 25 feet wide, and 200, 250, and 300 feet long respectively. In each case the total height of the diagram represents 100 per cent of area. The height from the bottom border to the first line represents the percentage of total area extracted inside the panels; the height from the first line to the second represents the percentage extracted in entries outside the panels; the height from the second line to the third represents the percentage lost in entries outside the panels; the height from the third line to the fourth represents the percentage lost in pillars outside the panels; and the height from the fourth line to the top of the figure represents the percentage lost inside the panels. As these diagrams are based only upon results with 25-foot rooms on 50-foot centers, no changes of percentage of extraction are involved that are dependent upon change of room width.

These diagrams illustrate the final disposal of the coal in the area considered; they show the amounts won and lost, and the general distribution of extraction and losses. The coal extracted comes from panels and from entries outside the panels, the larger part coming from the panels. As the number of rooms per entry increases, the amount of coal taken from the panels increases, but in the example considered it remains fairly constant after the number of rooms per entry reaches about twenty.

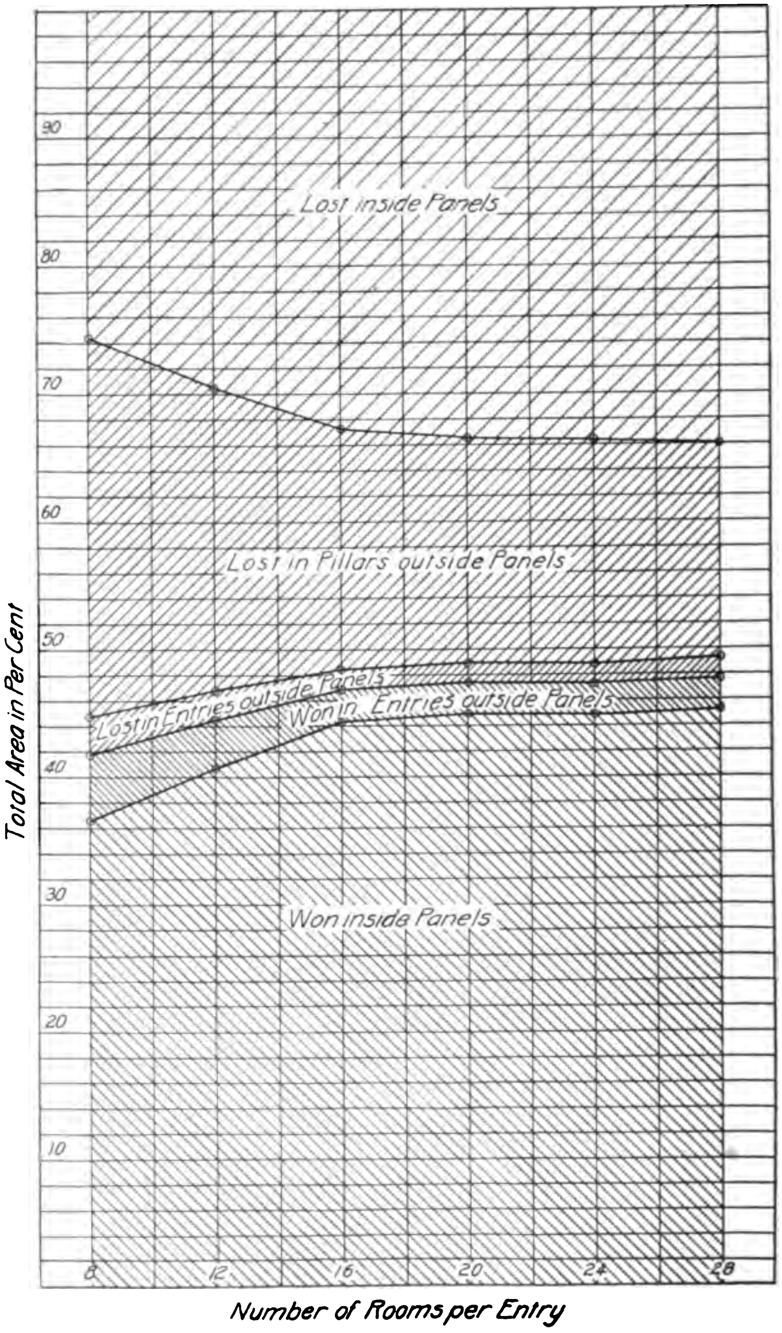

FIG. 7. DISTRIBUTION OF EXTRACTION AND LOSS FOR ROOMS 200 FEET LONG, 25 FEET WIDE, ON 50-FOOT CENTERS

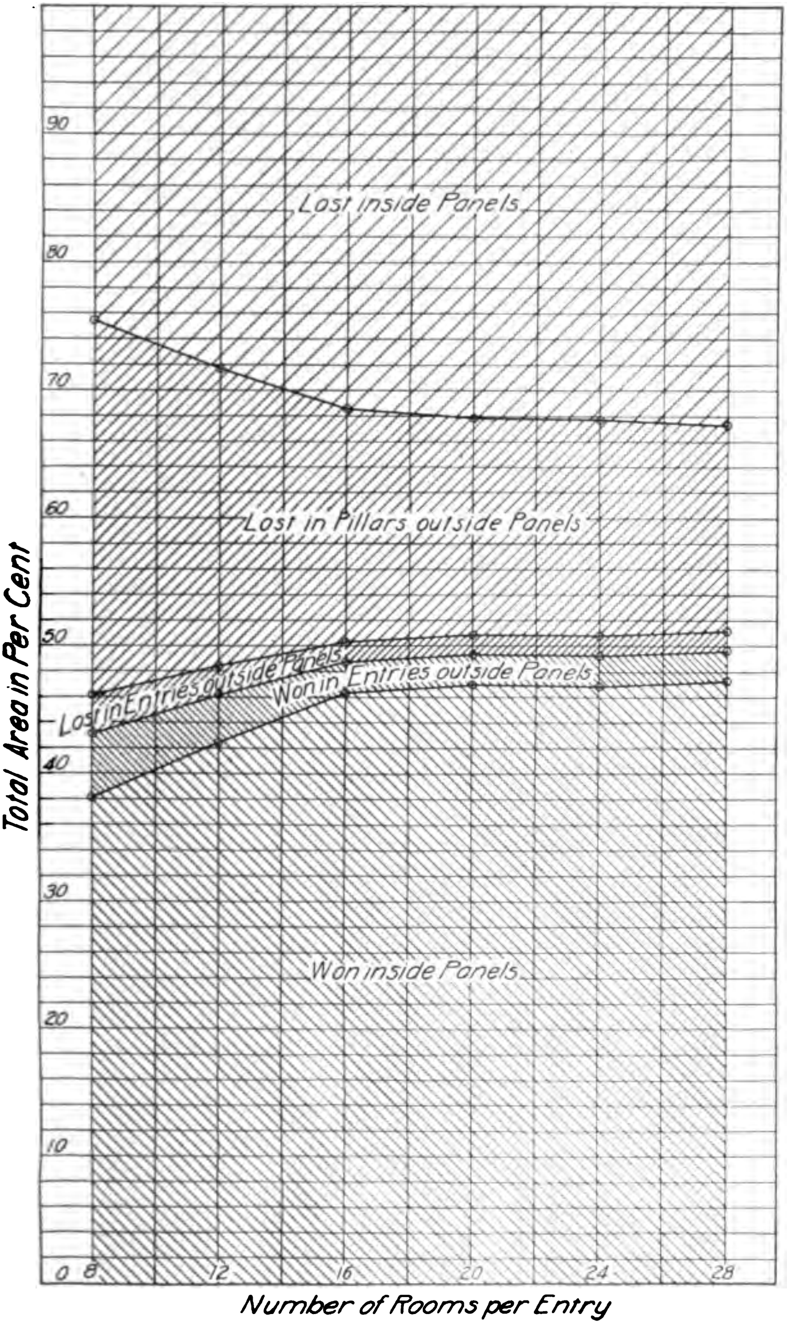

FIG. 8. DISTRIBUTION OF EXTRACTION AND LOSS FOR ROOMS 250 FEET LONG, 25 FEET WIDE, ON 50-FOOT CENTERS

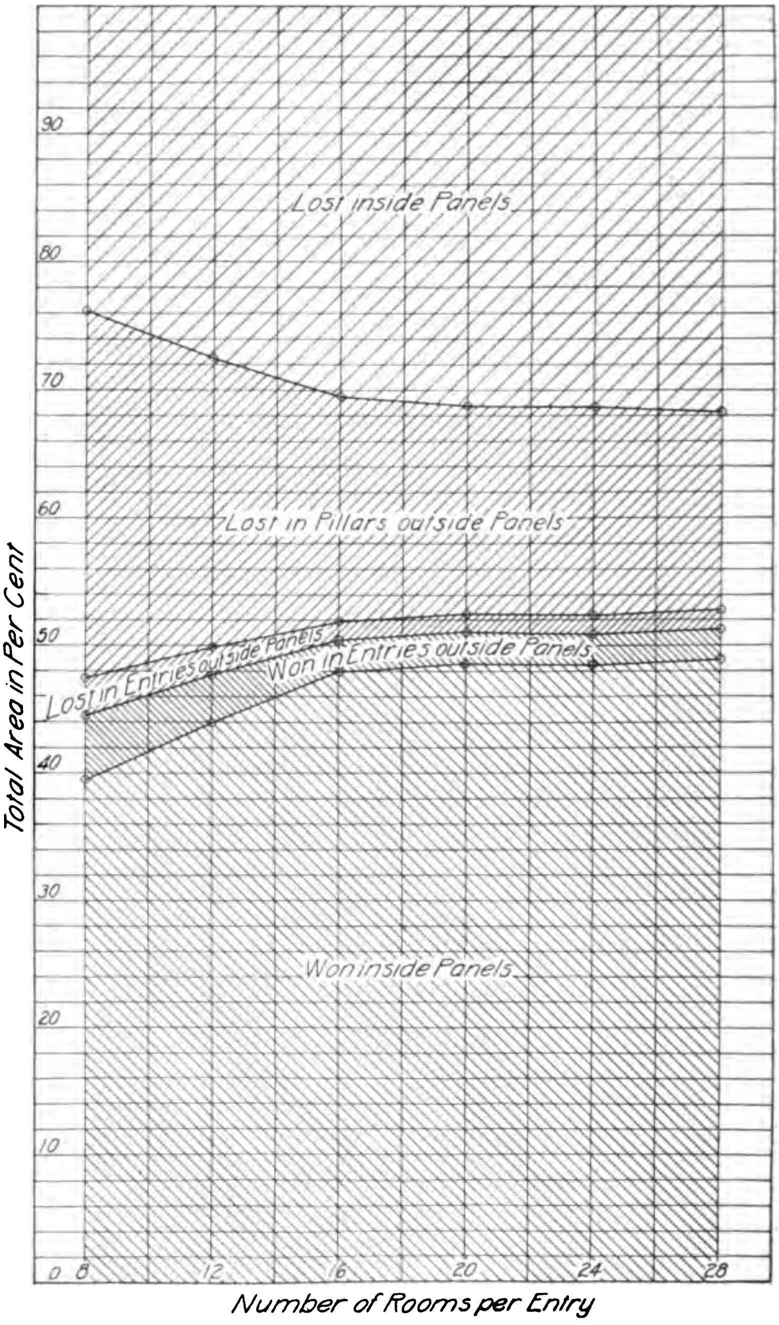

FIG. 9. DISTRIBUTION OF EXTRACTION AND LOSS FOR ROOMS 300 FEET LONG, 25 FEET WIDE, ON 50-FOOT CENTERS

With the increase of number of rooms per entry there is a slight decrease in the percentage extracted from entries outside the panels and also a slight decrease in the coal lost in entries outside the panels, both decreases being due to reduction of area occupied by entries. It is shown plainly that the amount of coal lost and won in entries is not large in any case.

One thing clearly indicated is that the increased extraction which accompanies increase of number of rooms per entry is due largely to a decrease in loss in pillars outside the panels; that is, to decrease of space occupied by barrier pillars. It is also shown that this decrease is much less rapid after rather than before approximately 16 rooms per entry have been reached and that beyond 20 rooms per entry there is very little change.

The fact that the lines become nearly horizontal after 16 to 20 rooms per entry have been reached shows that no material increase of percentage of extraction can be made by further increasing the number of rooms per entry. Comparison of the three diagrams shows also that very slight additional extraction can be accomplished by lengthening rooms. It follows, therefore, that the only two ways of increasing extraction are by increase of ratio of room width to pillar width and by extraction of pillar coal. These two methods may be said to reduce the loss in room pillars, but by entirely different means. It has been proved by experience that attempts to increase room width at the expense of pillar width are dangerous, and it is believed that the greatest ratio of room width used in the preceding discussion,—namely, four to one, considerably exceeds any limit which would ordinarily be safe for operation. It therefore follows that increase of extraction can be attained only by adopting some method for removing pillar coal after the rooms have been driven.

26. *Other Methods of Computation.*—It is recognized that the inclusion of the main entry and its barrier pillars in the tract considered gives percentages of extraction that must be changed somewhat if applied to larger areas, because the ratio of barrier pillar to total area is greater than would be the case in a larger area. This error could be avoided to some extent by choosing the part of the mine to be examined so that the main entry would not be included; thus the computed extraction would be a little too high.

Irregularities due to the limiting of the area considered could be avoided by a method of computation suggested by C. W. Hippard. Instead of a unit area of 160 acres, the area served by a pair of room entries with half of the adjoining cross entry and barriers and half of the surrounding fire pillars is considered. Such an area, which may be called a unit panel, is shown enclosed by dotted lines in Fig. 10.

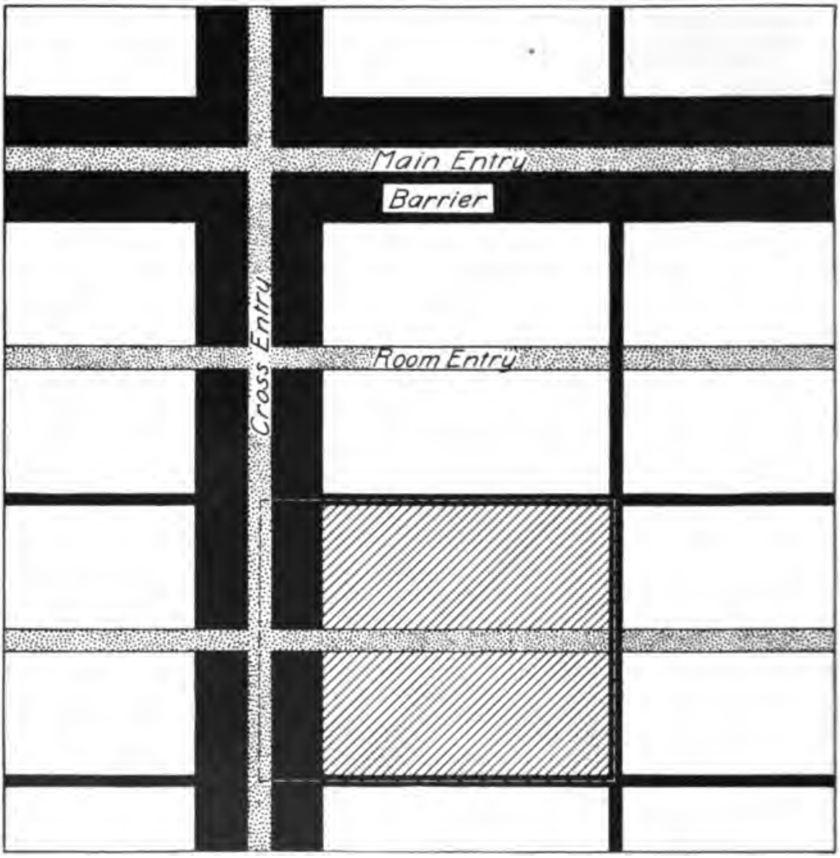

FIG. 10. UNIT PANEL

A single panel with its proper share of cross entry, barriers, and fire pillars is considered a true sample of the mine. The area of the tract considered is not constant, but changes with length of rooms, width of rooms, and number of rooms per panel. As the proportion of the main entry and barriers properly chargeable to this unit area changes with the size of the tract considered, it is best not to include main entry and barriers in the calculation. Calculated percentages of extraction are then a little too high.

The following computation by this method illustrates the procedure. The dimensions considered are those given on page 18.

Area of panel except room entry, (p. 21), 287,500 square feet
Percentage of extraction in room-and-pillar area, (p. 21), 59.91 per cent
Area excavated in panel except room entry,
$0.5991 \times 287{,}500 =$ . . . . . . 172,241 square feet
Area occupied by room entry,
$44 \times 675 = 29{,}700$ square feet
Percentage of extraction in room entry,
(p. 21), 62.12 per cent
Area excavated in room entry,
$0.6212 \times 29{,}700 =$ . . . . . . 18,450 square feet
Area occupied by cross entry,
$\frac{1}{2} \times 49 \times 564 = 13{,}818$ square feet
Percentage of extraction in cross entry,
(p. 22), 57.48 per cent
Area excavated in cross entry,
$0.5748 \times 13{,}818 =$ . . . . . . 7,943 square feet

Total area excavated . . . . . 198,634 square feet
Area of tract considered,
$564 \times 712 = 401{,}568$ square feet
Percentage of extraction

$$\frac{198{,}634 \times 100}{401{,}568} = 49.47 \text{ per cent}$$

This result is 3.14 per cent greater than the extraction calculated by the method described on pages 18 to 24, the difference being due to the exclusion of the main entry and its barriers in the unit panel method. Calculations by the latter method with other numbers of rooms per entry give the following results:

	Extraction
16 rooms per entry	50.98 per cent
20 rooms per entry	51.96 per cent
24 rooms per entry	52.64 per cent
28 rooms per entry	53.14 per cent

The percentages thus obtained agree closely with those previously calculated.

APPENDIX I

COST OF PRODUCTION AND THE PERCENTAGE OF EXTRACTION IN FULTON COUNTY

WORK OF J. C. QUADE

An investigation of the percentage of extraction in the Fulton County field has been made by J. C. Quade, Chief Engineer of the Big Creek Coal Company and of the Saline County Coal Company. The results of this investigation are in part reproduced in the following pages through the courtesy of Mr. Quade who has reviewed the summary.

These computations were made chiefly to find means of reducing the cost of production, the computation of extraction being incidental but necessary to the computation of cost. The results show that the highest percentage of extraction accompanied the lowest cost of production per thousand tons.

In making computations of cost no attention was paid to the total cost of production, but only to the items which would be directly modified by changes of dimensions of workings. The values of these were determined in part by the prices fixed in the agreement with the United Mine Workers and in part by practice in the Fulton County field.

The items considered in the computation are:

Yardage paid for narrow work.
Room turning.
Switch laying.
Wood track.
Props.

These items are intended to cover labor and materials not directly employed in the extraction of coal. The materials considered are those from which little if any salvage is expected. Such large items of expense as mining, haulage, ventilation, drainage, interest on capital and amortization are omitted because they are little affected by the changes contemplated. The expense of maintaining the various items considered is small in comparison with the total cost of production, but the calculation includes those items which are most immediately and completely affected by changes in the dimensions of workings.

The method of computation was determined by the fact that the company had an area of 160 acres in Fulton County which was soon to be developed. The tract was in the form of a square with public roads on two sides, coal owned by the company on the third side, and coal not owned by the company on the fourth side. It was therefore necessary to leave pillars along three borders but not along the fourth. This tract was laid out with two main entries, and with six cross entries where 210-foot rooms are considered and seven cross entries where 180-foot rooms are considered as shown in Fig. 11. The form of the field and the necessity of leaving boundary pillars in-

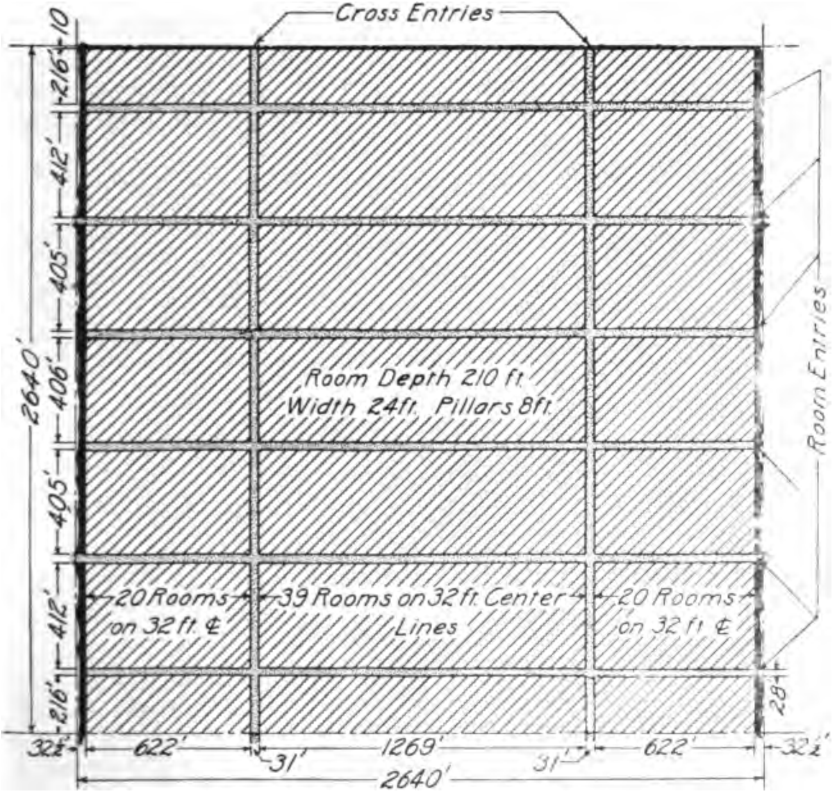

Fig. 11. Map of 160 Acres for J. C. Quade's Computation

fluenced both the lengths of entries and the number of rooms. The coal lying east and west of this tract was developed later; hence two pairs of room entries were extended through the boundary pillars on each side to become the cross entries of the newer developments.

Only two lengths of rooms were considered: 180 feet because that length was then being used by the company, and 210-feet because experience had shown this to be the maximum length for a room which could commonly be kept open for the time required to complete extraction without considerable expense for retimbering.

An analysis of the fixed costs in the district in which the mine is located showed that the yardage paid for narrow work in room cross-cuts was responsible for a considerable share of these costs. This yardage could be eliminated by driving room cross-cuts wider than the limit for which yardage is paid, or could be reduced by decreasing the length of the room cross-cuts by making pillars narrower. The calculations involve both methods.

The following items of cost are based upon conditions in the Fulton County field at the time when the calculations were made.

Mining rates fixed by agreement between the United Mine Workers and Operators.

		Per Yard
Pick rate,	8-foot entries	$1.82
	12-foot entries	1.24
	16-foot entries	0.00
Room turning		4.55
Machine rate,	8-foot entries	1.46
	12-foot entries	1.00
	16-foot entries	0.00
Room turning		3.64

Items fixed by the experience of the company in the Fulton County Field.

Switch laying and ties	$4.00 per room
Props	0.005 per square foot
Each prop costing $0.06 and supporting an average of 12 square feet of roof.	
Wood rails, 1.3 times the length of the room at $22.00 per 1000 board feet	6.25 for 180-foot room 7.45 for 210-foot room
Track laying and ties	0.10 per foot
Brushing and timbering entries, approximately $3.00 per foot for 25 per cent of the length of the entry	0.75 per foot

Some of the figures given would not be applicable at present, but the method used can be applied by changing the expense of various items to correspond with changes in conditions.

In computing the production to be expected from different dimensions of workings, it is assumed that 25 cubic feet of coal in place are equivalent to one ton, and that 5.70 square feet of area are equivalent to a production of one ton if proper allowances are made for the thickness of the coal, which averages 4 feet, 10 inches, and for the waste which always accompanies mining. It is assumed that rooms from adjoining cross entries are driven through until they meet and that five cross-cuts are driven in the length of the two 180-foot rooms and six in the length of the two 210-foot rooms. This arrangement accounts for the average number of cross-cuts being 2½ for a 180-foot room.

The following tables give the essential data on which the calculations are based. Table 8 gives the number of rooms in 160 acres, for each room width and for each pillar width, for rooms 180 feet long and 210 feet long. The total number of rooms varies less regu-

TABLE 8

NUMBER OF ROOMS IN 160 ACRES

Room Width (Feet)	Room Length and Centers	Pillar Width							
			7	8	9	10	11	12	16	20
20	180 Centers 210	1330 26 1140	1298 27 1104	1232 28 1056	1204 29 1032	1162 30 996	1120 31 960	1106 32 948	960 36 840	882 40 756
21	180 Centers 210	1298 27 1104	1232 28 1056	1204 29 1032	1162 30 996	1120 31 960	1106 32 948	1050 33 960	952 37 816	840 41 720
22	180 Centers 210	1232 28 1056	1204 29 1032	1162 30 996	1120 31 960	1106 32 948	1050 33 900	1036 34 888	938 38 804	840 42 720
23	180 Centers 210	1204 29 1032	1162 30 996	1120 31 960	1106 32 948	1050 33 900	1036 34 888	994 35 852	896 39 768	826 43 708
24	180 Centers 210	1162 30 996	1120 31 960	1106 32 948	1050 33 900	1036 34 888	994 35 852	980 36 840	882 40 756	784 44 672
25	180 Centers 210	1120 31 960	1106 32 948	1050 33 900	1036 34 888	994 35 852	980 36 840	952 37 816	840 41 720	784 45 672
26	180 Centers 210	1106 32 948	1050 33 900	1036 34 888	994 35 852	980 36 840	952 37 816	938 38 804	840 42 720	770 6 6

larly than the dimensions, because no fractional rooms were considered, but only such arrangements of whole rooms as would most nearly completely cover the 160-acre tract.

TABLE 9
AREA OF ROOMS[1] AND TONS OF COAL PER ROOM[2]

Width of Rooms (Feet)	Length 180 Feet		Length 210 Feet	
	Area (Square Feet)	Tons	Area (Square Feet)	Tons
20	3382	593.33	3982	698.60
21	3546.5	622.16	4176.5	732.32
22	3711	651.05	4371	766.84
23	3875.5	679.91	4565.5	800.96
24	4040	708.77	4760	835.08
25	4204.5	737.63	4954.5	869.20
26	4369	766.50	5149	903.33

[1] Not including cross-cuts.

[2] 5.70 square feet of 4-foot, 10-inch coal per ton, allowing for waste.

TABLE 10
AREA OF ROOM CROSS-CUTS (PER CROSS-CUT), TONS OF COAL PRODUCED AND YARDAGE COST[1]

Width of Pillar (Feet)	8-ft. Cross-Cut			12-ft. Cross-Cut			16-ft. Cross-Cut		
	Area (Square Feet)	Tons of Coal at 5.70 Square Feet per Ton	Yardage Cost at 60⅔ cents per Foot	Area (Square Feet)	Tons of Coal at 5.70 Square Feet per Ton	Yardage Cost at 41⅓ cents per Foot	Area (Square Feet)	Tons of Coal at 5.70 Square Feet per Ton	Yardage Cost 0.00
6	48	8.41	$3.64	72	12.62	$2.48	96	16.84	....
7	56	9.83	4.25	84	14.74	2.89	112	19.65	....
8	64	11.23	4.85	96	16.84	3.31	128	22.46	....
9	72	12.63	5.46	108	18.94	3.72	144	25.26	....
10	80	14.03	6.07	120	21.05	4.14	160	28.07	....
11	88	15.44	6.67	132	23.16	4.55	176	30.88	....
12	96	16.84	7.28	144	25.66	4.96	192	33.68	....
16	128	22.46	9.71	192	33.69	6.61	256	44.91	....
20	160	28.07	12.13	240	42.10	8.27	320	56.14	....

[1] Yardage for narrow work, pick rate:
8 feet wide $1.82 = 60⅔ cents per foot.
12 feet wide 1.24 = 41⅓ cents per foot.
16 feet wide 0.00 = 00 cents per foot.

Table 9 gives the areas of rooms, not including cross-cuts, and the tons of coal per room calculated on the basis of 5.70 square feet per ton.

Table 10 gives for each cross-cut the area, the tons of coal produced, and the yardage cost. The number of tons produced is calculated from the area on the basis of 5.70 square feet per ton. The yardage cost is calculated from the prices fixed in the agreement with the United Mine Workers. Only the rate for pick mining was considered as machines were not used much in the district when the data were compiled. The ratio between yardage cost for 8-foot and 12-foot cross-cuts is the same for pick work as for machine work; therefore if the rates for machine work were substituted in place of those for pick work in the calculations, the results would show a decrease in the total expense, but the percentage of the total expense for narrow work saved by the reduction in the amount of this work would remain the same. Three widths of cross-cuts were considered: 8 feet, which is assumed to be the minimum practical width (this is the minimum width for which a yardage price is fixed in the agreement with the United Mine Workers); 12 feet, which is considered an average; and 16 feet, which, according to the agreement, is wide work and does not require extra compensation.

TABLE 11
TOTAL CROSS-CUT YARDAGE COST PER ROOM

Width of Pillar (Feet)	8-ft. Cross-Cuts		12-ft. Cross-Cuts	
	180-ft. Room 2½ Cross-Cuts	210-ft. Room 3 Cross-Cuts	180-ft. Room 2½ Cross-Cuts	210-ft. Room 3 Cross-Cuts
6	$ 9.10	10.92	6.20	7.44
7	10.63	12.75	7.23	8.67
8	12.13	14.55	8.28	9.93
9	13.65	16.38	9.30	11.16
10	15.18	18.21	10.35	12.42
11	16.68	20.01	11.38	13.65
12	18.20	21.84	12.40	14.88
16	24.28	29.12	16.53	19.84
20	30.33	36.39	20.67	24.80

Table 11 gives the total cross-cut yardage cost per room, obtained by multiplying the cost per cross-cut as given in Table 3 by the proper number of cross-cuts.

TABLE 12

TONS OF COAL IN CROSS-CUTS PER ROOM

Width of Pillar (Feet)	180-ft. Room 2½ Cross-Cuts		210-ft. Room 3 Cross-Cuts	
	8-ft. Cross-Cut	16-ft. Cross-Cut	8-ft. Cross-Cut	16-ft. Cross-Cut
6	21.02	42.04	25.23	50.46
7	24.58	49.16	29.49	58.98
8	28.07	56.14	33.69	67.38
9	31.57	63.14	37.89	75.78
10	35.08	70.16	42.09	84.18
11	38.60	77.20	46.32	92.64
12	42.09	84.18	50.52	101.04
16	56.15	112.30	67.38	134.76
20	70.17	140.34	84.21	168.42

TABLE 13

COST OF PROPS FOR ROOM AND CROSS-CUTS AT ONE-HALF CENT PER SQUARE FOOT, 180-FOOT ROOMS

Width of Room (Feet)	Prop Cost for Room	Width of Pillar								
		6	7	8	9	10	11	12	16	20
		Prop Cost for Cross-Cuts per Room								
		$0.90	$1.05	$1.20	$1.35	$1.50	$1.65	$1.80	$2.40	$3.00
		Prop Cost for Room and Cross-Cuts								
20	$16.91	$17.81	$17.96	$18.11	$18.26	$18.41	$18.56	$18.71	$19.31	$19.91
21	17.73	18.63	18.78	18.93	19.08	19.23	19.38	19.53	20.13	20.73
22	18.56	19.46	19.61	19.76	19.91	20.06	20.21	20.36	20.96	21.56
23	19.38	20.28	20.43	20.58	20.73	20.88	21.03	21.18	21.78	22.38
24	20.20	21.10	21.25	21.40	21.55	21.70	21.85	22.00	22.60	23.20
25	21.02	21.92	22.07	22.22	22.37	22.52	22.67	22.82	23.42	24.02
26	21.85	22.75	22.90	23.05	23.20	23.35	23.50	23.65	24.25	25.85

Table 12 gives the amount of cross-cut coal in tons per room, obtained by dividing the areas of cross-cuts by 5.70, the number of square feet of area equivalent to a production of one ton, and multiplying by the proper number of cross-cuts per room.

TABLE 14

COST OF PROPS FOR ROOM AND CROSS-CUTS AT ONE-HALF CENT PER SQUARE FOOT, 210-FOOT ROOMS

Width of Room (Feet)	Prop Cost for Room	Width of Pillar								
		6	7	8	9	10	11	12	16	20
		Prop Cost for Cross-Cuts per Room								
		$1.08	$1.26	$1.44	$1.62	$1.80	$1.98	$2.16	$2.88	$3.60
		Prop Cost for Room and Cross-Cuts								
20	$19.91	$20.99	$21.17	$21.35	$21.53	$21.71	$21.89	$22.07	$22.79	$23.51
21	20.88	21.96	22.14	22.32	22.50	22.68	22.86	23.04	23.76	24.48
22	21.86	22.94	23.12	23.30	23.48	23.66	23.84	24.02	24.74	25.46
23	22.83	23.91	24.09	24.27	24.45	24.63	24.81	24.99	25.71	26.43
24	23.80	24.88	25.06	25.24	25.42	25.60	25.78	25.96	26.68	27.40
25	24.77	25.85	26.03	26.21	26.39	26.57	26.75	26.93	27.65	28.37
26	25.75	26.83	27.01	27.19	27.37	27.55	27.73	27.91	28.63	29.35

Tables 13 and 14 give the cost of props for a room and its cross-cuts for each width of room from 20 to 26 feet and for each width of pillar from 6 feet to 20 feet. The cost in cents is obtained by dividing the cost per prop, taken as six cents, by the area supported by one prop, 12 square feet, these being figures based upon the experience of the company.

$$\frac{\text{Cost per prop}}{\text{Square feet of area supported}} = \frac{6}{12} = \frac{1}{2} \text{ cent per square foot, or for 1 room}$$

$$\frac{\text{Number of square feet in room}}{2} = \text{cost in cents}$$

In each table the cost of props per room is given at the left, the cost of props for cross-cuts is given at the top, and the cost of props for the rooms and cross-cuts together is given in the body of the table.

These tables of prop costs are computed on the assumption that all cross-cuts are 12 feet wide. In the comparison of total costs, this assumption introduces a small error because this comparison is between 8-foot and 16-foot cross-cuts. To obtain correct values it would be necessary to make allowance for the error thus introduced by decreasing the prop cost with 8-foot cross-cuts and increasing it with 16-foot cross-cuts. The difference between these two costs would accordingly be decreased, this difference being the saving effected by the use of 16-foot cross-cuts. In rooms of 180 feet long with 6-foot pillars, the error introduced by the use of this average figure amounts to 94 cents per thousand tons. In rooms 210 feet long with 20-foot pillars, the error is $2.09 per thousand tons. These errors are the extremes, and the errors when other dimensions of rooms and pillars are used lie between these two. Since the pillar width selected as the best was small,—viz., 8 feet, the effect of the assumption of 12-foot cross-cuts was small.

The specimen computations given show the methods employed. All essential data are contained in the preceding tables and the calculations involve only the arrangement of these data in such form as clearly to represent the facts and permit comparisons between percentages of extraction and costs of production for different dimensions of rooms.

SPECIMEN COMPUTATIONS

COAL PRODUCED

Rooms and Cross-Cuts

Room width	20 feet
Room length	210 feet
Pillar width	6 feet
Total number of rooms in 160 acres	1140
Room coal	698.60 tons
Coal from 8-foot cross-cuts	25.23 tons
Total coal from room and 8-foot cross-cuts	723.83 tons
Coal from additional 8-feet of cross-cuts	25.23 tons
Total coal per room and 16-foot cross-cuts	749.06 tons

Coal from 160 Acres

	Tons
Total room coal = 698.60 × 1140 =	796,404
Total coal from 8-foot cross-cuts = 25.23 × 1140 =	28,762
Coal from main entry and cross-cuts	16,716
Coal from cross entries and cross-cuts	47,836
Total	889,718
Additional coal from 16-foot cross-cuts	28,762
Grand total	918,480

COST AND SAVING

Fixed Room Charges per Room

Room turning	$ 4.55
Switch-laying and ties	4.00
Wood rails	7.45
	$16.00
Props per room and 8-foot cross-cut	21.00
	$37.00
Room cross-cut yardage	10.92
Total for room and cross-cuts	$47.92

Total Fixed Room Charges per 160 Acres

Room turning; switch laying and ties; wood rails, props	= $37.00 × 1140	= $42,180.00
Room cross-cut yardage	10.92 × 1140	= 12,448.80
Total fixed room charges		$54,628.80

Saving by making cross-cuts 16 feet wide . . . .
. . . $12,448.80 = 22.79 per cent fixed room charges with 8-foot cross-cuts

Total Cost for Items Considered

Total fixed room charges	$ 54,628.80
Main entry and cross-cuts, 11,910 feet narrow work at $0.61 per foot	7,265.10
Cross entries and cross-cuts, 34,080 feet narrow work at $0.61 per foot	20,788.80
Track laying	4,176.00
Brushing and timbering	31,320.00
Total cost for 160 acres	$118,178.70
Total cost for 160 acres with 16-foot room cross-cuts, 118,178.70 − 12,448.80 =	$105,729.90

Cost per 1,000 tons with 8-foot room cross-cuts $\frac{118,178.70}{889.718} =$	132.83
Cost per 1000 tons with 16-foot room cross-cuts $\frac{105,729.90}{918.480} =$	115.11
Saving per 1000 tons with 16-foot room cross-cuts*	17.72

---

*The cost per 1000 tons mined is less by one method than by the other, but the quantity of coal considered is greater in the case of 16-foot room cross-cuts by the 28,762 tons gained in the additional 8 feet of cross-cut width.

The accompanying sets of diagrams, Figs. 12 and 13, show the most important points in connection with the percentage of extraction and the cost of production, so far as the latter is determined by the limited elements considered, for all room widths from 20 to 26 feet and for pillar widths of 6, 9, 12, 16, and 20 feet with 210-foot rooms and for 6-foot pillar widths with 180-foot rooms.

Three diagrams in each set are concerned with quantity of production. Diagram *A* gives the number of rooms in 160 acres; diagram *B,* the amount of coal produced per room and cross-cut; and diagram *C* the total amount of coal produced. This total production includes, not only coal taken from rooms and their cross-cuts, but also coal taken from entries and entry cross-cuts.

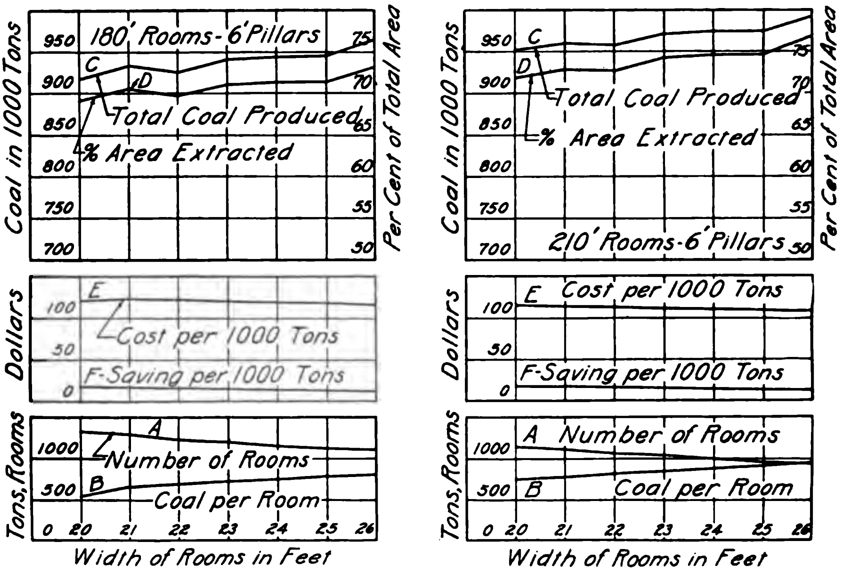

Fig. 12. Number of Rooms per Entry, Coal per Room, Total Coal from 160 Acres, Percentage of Area Excavated, Cost per 1000 Tons, Saving per 1000 Tons

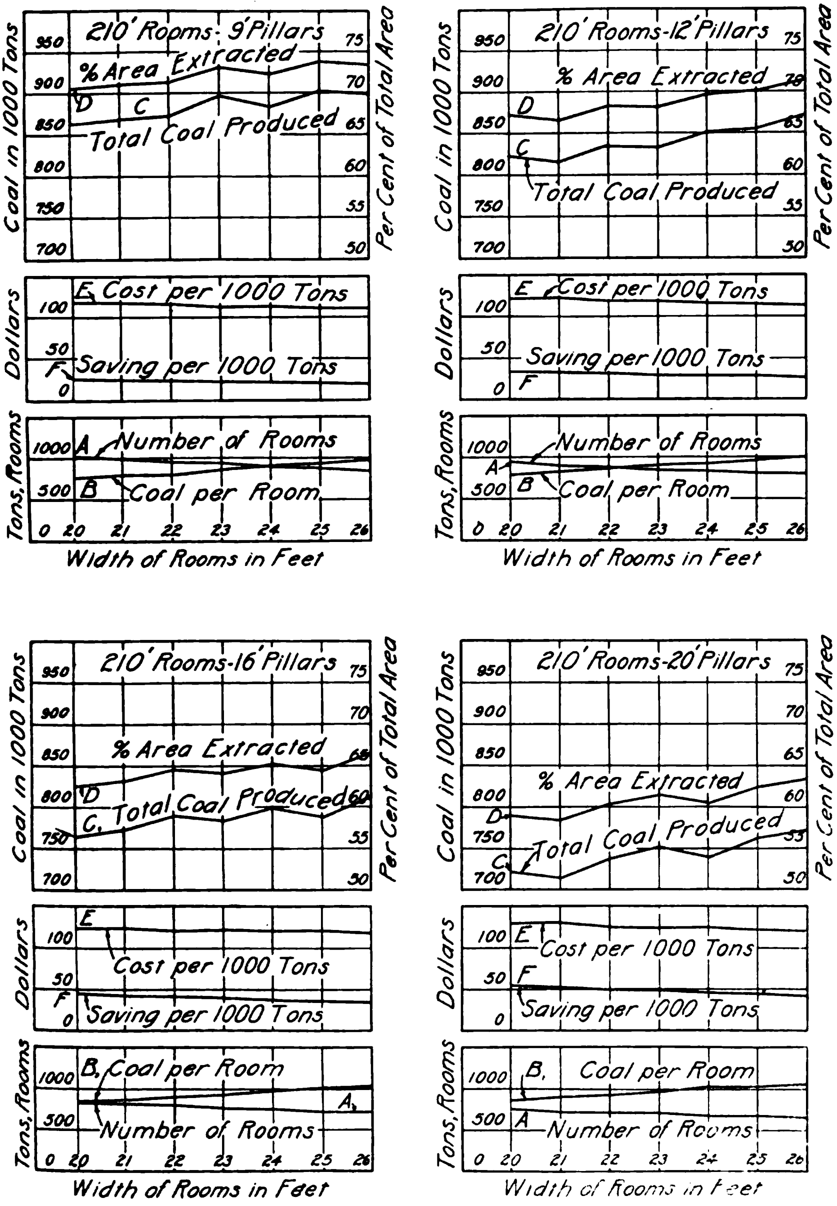

FIG. 13. NUMBER OF ROOMS PER ENTRY, COAL PER ROOM, TOTAL COAL FROM 160 ACRES, PERCENTAGE OF AREA EXCAVATED, COST PER 1000 TONS, SAVING PER 1000 TONS

Diagram *D* shows the percentage of extraction, based on the area excavated instead of on the number of tons produced as calculated by Mr. Quade, in order that this portion of the discussion may be brought into direct comparison with the preceding part of the bulletin. The values for the percentage of extraction on the area basis are slightly higher than they would be if computed from tonnage produced because of the waste in mining and the presence of slips and horse backs. If these losses did not exist, the values of the percentage of extraction obtained by the two methods would be the same, because the entire thickness of the coal bed is extracted. A comparison of these two methods in rooms 20 by 210 feet with 12-foot pillars and 16-foot cross-cuts gave an extraction on the basis of tons produced of 61.05 per cent and on the basis of area excavated of 67.28 per cent.

The diagram for total output is irregular, because its shape is determined by that for the number of rooms. This number does not change uniformly with change of width of rooms, but, for each set of dimensions, the number of rooms was selected which was most suitable for working out the 160-acre tract to be developed. The total output is the sum of the tonnage of coal produced in rooms and cross-cuts, and in entries. Since the output from entries varies only with the number of cross entries which in turn is affected by a change in the length of rooms, the total output varies only with the number of rooms or with the output from a room and its cross-cuts. The latter quantity varies regularly with the change of room width, and therefore irregularities in the total output are entirely due to irregularities in the number of rooms. The curve for total output is drawn to a scale which makes its irregularities more prominent than those in the curve for the number of rooms.

Diagram *E* shows the cost per thousand tons for the limited number of items considered. The line drops as that showing total output rises, thus showing that the cost of production decreases as the output from a given area increases.

Diagram *F* shows the saving per thousand tons accomplished by increasing the width of room cross-cuts from 8 feet to 16 feet, and eliminating room cross-cut yardage. Mr. Quade's computations were made with the object of determining this saving, and the adoption of the dimensions indicated by these calculations as being most economical has resulted in very large reduction in the cost of producing coal.

The dimensions selected were: room width 24 feet, pillar width 8 feet, cross-cut width 16 feet. The diagrams show that the cost would be lower and the extraction higher if narrower pillars could be used, but it was not practical to make them less than about 8 feet in width. This width is, however, necessary only near the entries; the pillars arc made gradually narrower towards the ends of the rooms, the percentage of extraction being thus increased. The extraction in these mines since the adoption of the new dimensions is between 70 and 75 per cent.

For purposes of comparison one set of diagrams is given which shows, for 180-foot rooms, the same items of production and cost as are given for 210-foot rooms. At the time when the computations were made rooms were being driven 180 feet long. The total output for the two lengths of rooms differs only slightly, but the cost of production is lower with the 210-foot room; hence that length was adopted as a standard.

The diagrams in Fig. 14 show the production of coal from different parts of the workings and emphasize the increase of production with increase of room width. Diagram *A* shows the production from rooms and 8-foot cross-cuts. Diagram *B* shows the sum of the tonnage of room and cross-cut coal and entry coal, the space between *A* and *B* representing the entry coal. The space between *B* and *C* shows the additional coal taken from 16-foot cross-cuts; therefore *C* shows the total coal produced from 160 acres with the longer dimension.

Fig. 15 is a graphical summary of costs and output for rooms 24 feet wide and 210 feet long. Diagrams *A, B, C,* and *D* show the effect of increase of pillar width on the tonnage produced. On these diagrams, *A* shows the number of rooms in 160 acres; *B* shows the output from rooms and 8-foot cross-cuts; *C* shows the additional output from entries; and *D* shows the additional output from the extra width of room cross-cuts. The diagram shows the decrease of output resulting from the decrease in the number of rooms, which accompanies increase of pillar width.

The items of cost considered in the investigation are shown in zones, of which the first is yardage cost for the main entry, the second yardage cost for the cross entries, the third track-laying cost for entries, the fourth brushing and timbering costs for entries, the fifth fixed room charges, and the sixth yardage cost of 8-foot room cross-cuts.

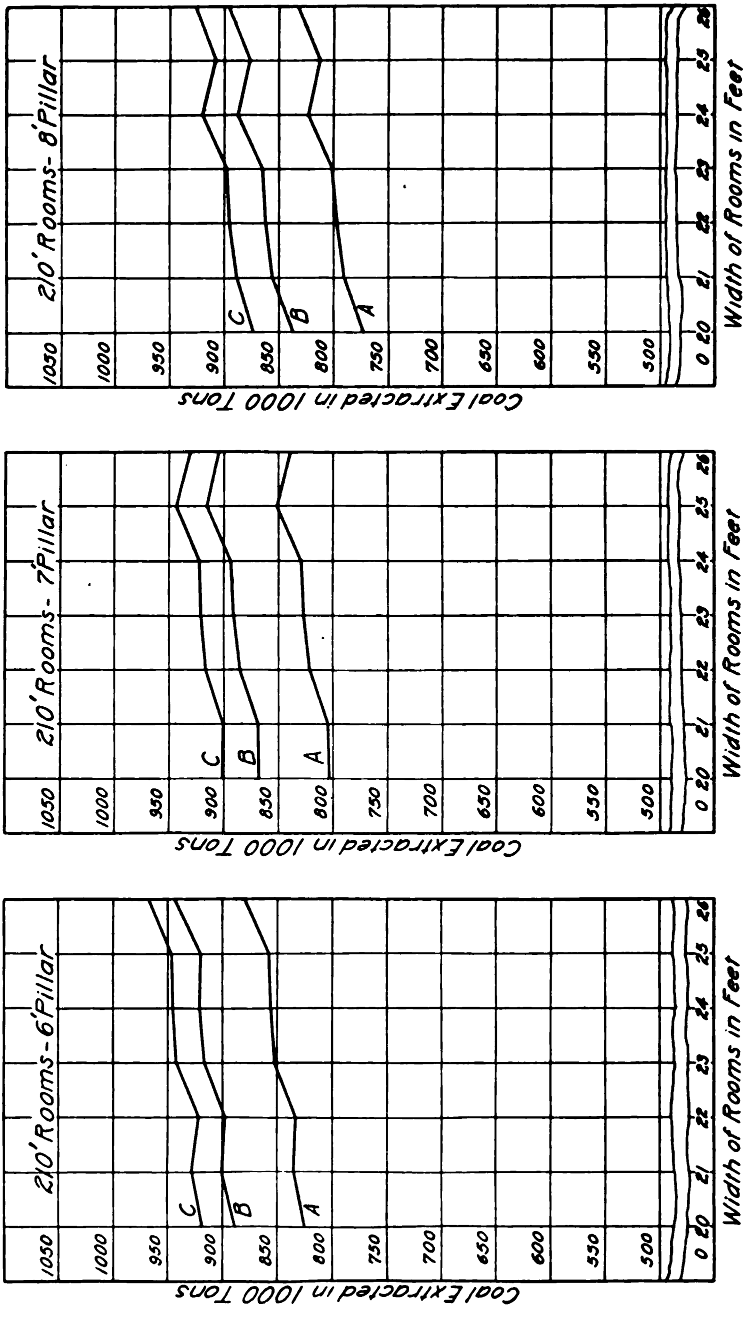

FIG. 14. PRODUCTION FROM ROOMS, ENTRIES, AND FROM ADDITIONAL CROSS-CUT WIDTH

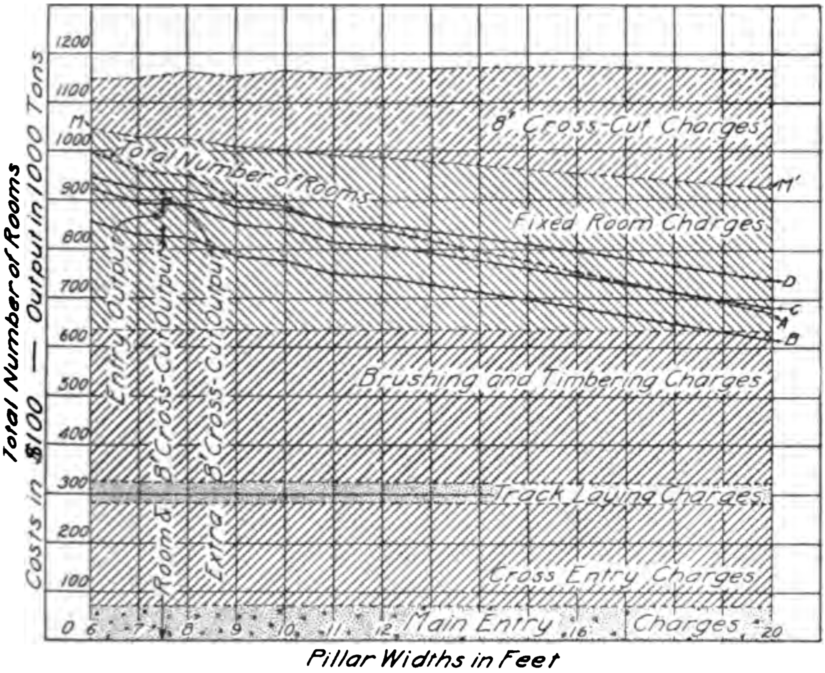

FIG. 15. SUMMARY OF COSTS AND OUTPUT FOR ROOMS 24 FEET WIDE AND 210 FEET LONG

The first four items change only when change in the length of rooms results in change of number of cross entries and therefore of total length of entries. The fifth item, fixed room charges, includes room turning, switch laying and ties, wood rails, and room props. The first three subdivisions change only with the number of rooms; the last increases with the width of rooms but decreases with their number. The sixth item, yardage cost of 8-foot cross-cuts, increases with pillar width because of the increased length of the cross-cuts. It is this last item of cost which is eliminated by increase of cross-cut width to 16 feet, leaving the line M M′ as the indication of total cost.

Some of the charts prepared by Mr. Quade are reproduced with some modification in Figs. 16, 17, and 18 to show more fully his method of presenting his conclusions.

Fig. 16 shows the effect of changes in cross-cut width on yardage cost for room cross-cuts and the amount of coal produced from them. The diagrams are based on 7-foot pillars with three cross-cuts per pillar. The arrangements of cross-cut widths in each pillar are: three 8 feet wide; one 8 feet and two 12 feet; three 12 feet; one 8 feet, one 12 feet, and one 16 feet; two 12 feet and one 16 feet; one 12 feet and two 16 feet, and three 16 feet. In the final computation of possible reductions of cost the only widths considered were 8 feet and 16 feet.

Fig. 17 gives in detail the cost per thousand tons as modified by certain changes in length and width of rooms, room pillars, entries, and room and entry cross-cuts.

The width of rooms considered, 25.36 feet, was the actual average made by 8 cuts of a breast-type chain coal cutting machine. This machine is commonly called a 3-foot machine, but the actual cut slightly exceeded this width. The costs of the various items considered are shown by the widths of the shaded bands, while the solid line *A B* shows the saving per thousand tons accomplished by the use of the

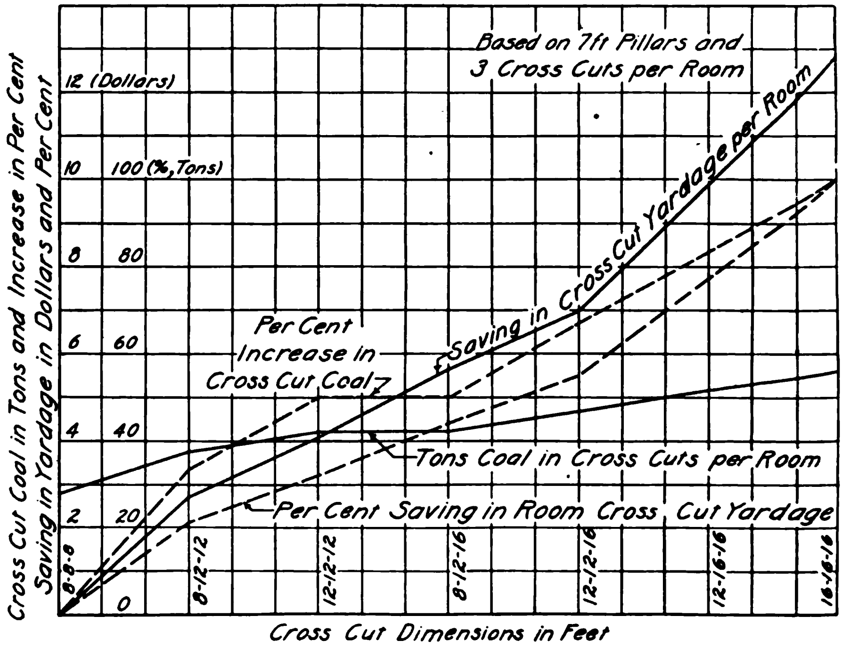

FIG. 16. EFFECT OF CHANGES IN CROSS-CUT WIDTH ON COST OF CROSS-CUTS AND COAL PRODUCED

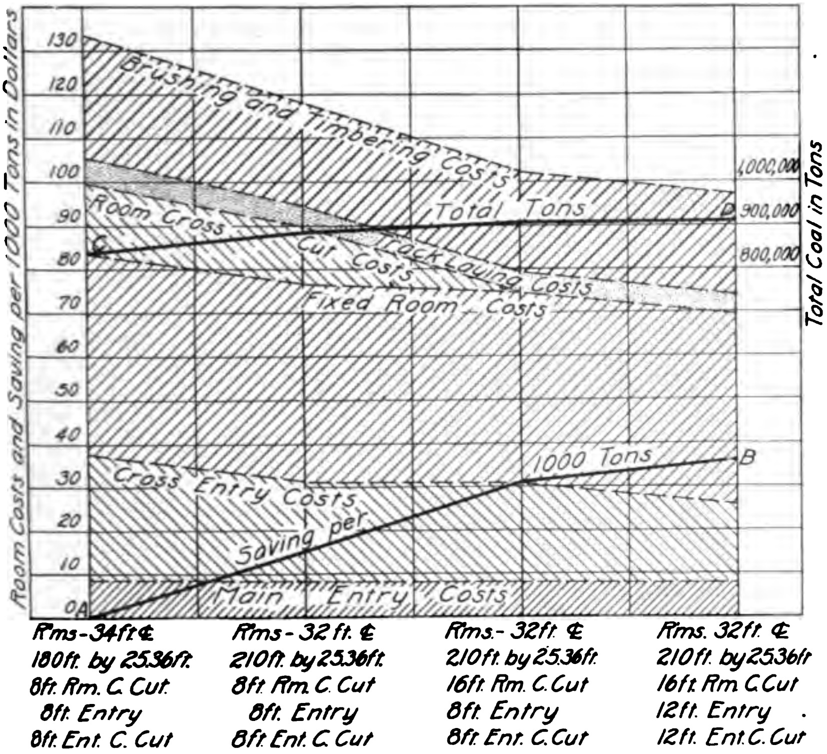

FIG. 17. CERTAIN FIXED CHARGES PER 1000 TONS, SAVING PER 1000 TONS, TOTAL OUTPUT FROM 160 ACRES

different changes in dimensions specified. The solid line *C D* shows the total coal produced from 160 acres with the same dimensions.

Fig. 18 is a summation of the items of room and room cross-cut costs considered and of total extraction and cost for 160 acres. This figure permits comparisons between results obtained by using different dimensions and shows the point of lowest cost and highest extraction. As in Fig. 14, room widths of 22.2 feet and 25.36 feet are due to the width of cut of the breast-type of coal cutting machines. The lower shaded areas show the cost per room for the various items considered as fixed room charges. Room turning and switch costs per room are not affected by any changes of dimensions. Wood rail cost increases with the length of rooms. Prop cost increases with both length and width of rooms. Cross-cut yardage cost is affected by room length,

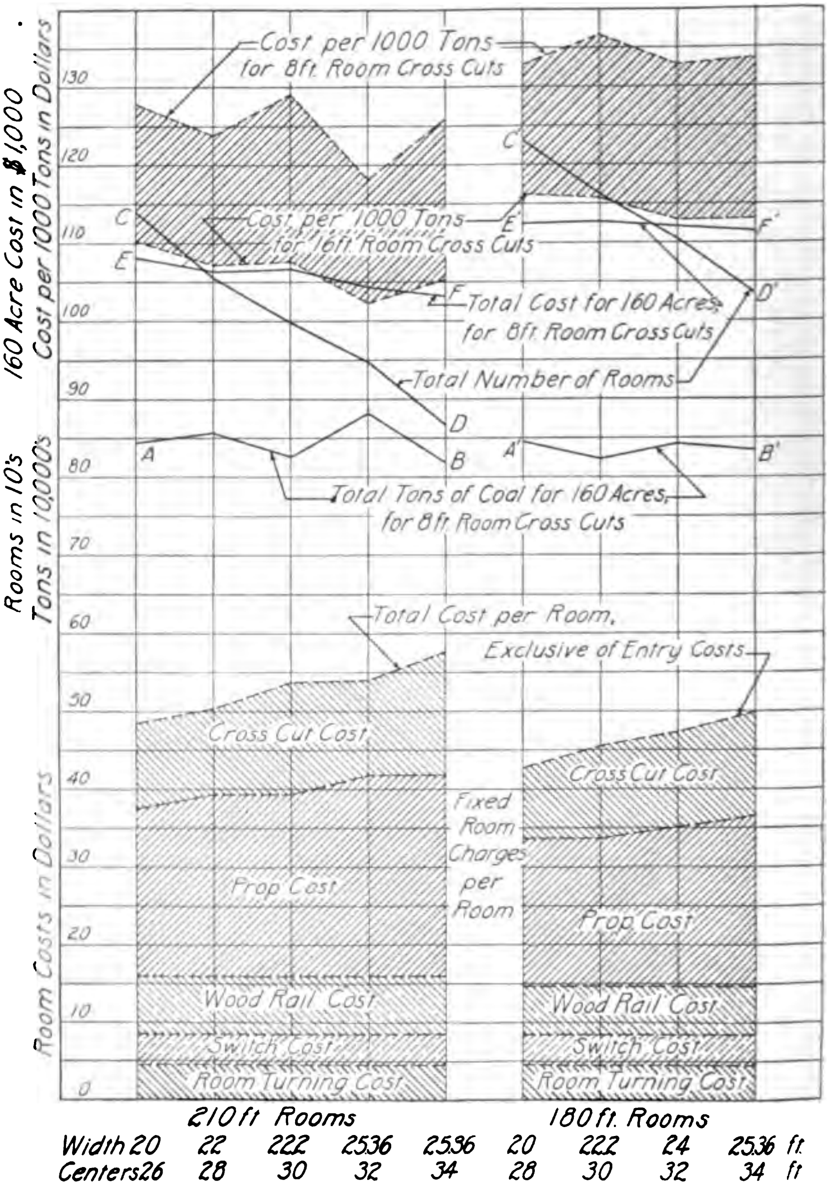

FIG. 18. SUMMATION OF FIXED CHARGES AND OUTPUT FOR 160 ACRES

which determines the number of cross-cuts, by cross-cut width and pillar width. The upper shaded areas show the difference in total cost per thousand tons, including entry costs, which results from the use of 8-foot and 16-foot room cross-cuts. The solid lines *A B* and *A′B′* show the total coal produced from 160 acres; *C D* and *C′D′* show the number of rooms in 160 acres; *EF* and *E′ F′* show the total cost for 160 acres when 8-foot cross-cuts are used.

The lowest total cost for 160 acres is shown to be reached with 210-foot rooms 25.36 feet wide on 34-foot centers, but the lowest cost per thousand tons and the highest extraction for 160 acres are shown to be reached with rooms of the same dimensions on 32-foot centers. Because of the common tendency of the miner to make his room somewhat wider than is planned, the latter dimensions might be approximately reached in practice if rooms were planned 24 feet wide on 32-foot centers. These dimensions, shown by Mr. Quade's work to be the best, were adopted for the company's mines in Fulton County with the result that the cost of producing coal was materially reduced. The percentage of extraction was raised from about 58 per cent to between 70 and 75 per cent which is unusually high for Illinois.

APPENDIX II

EXTRACTION AT DEWMAINE

WORK OF G. E. LYMAN

The results obtained with different dimensions of rooms in the Williamson County mines of the Madison Coal Corporation are shown in the following sketch and notes prepared by G. E. Lyman, formerly Chief Engineer and now General Superintendent of that company, and are published here with his courteous permission. The sketch, Fig. 19, shows the plan of operation followed at Dewmaine, north of Carterville. The only changes from the dimensions shown are in the width of room pillars, the two widths being 20 feet and 14 feet. The plans considered and compared, with each pillar width, involve the extraction of different quantities of pillar coal after the rooms have been finished.

The area considered is a restricted one, consisting only of a cross entry and a portion of the rooms turned from it. The tract con-

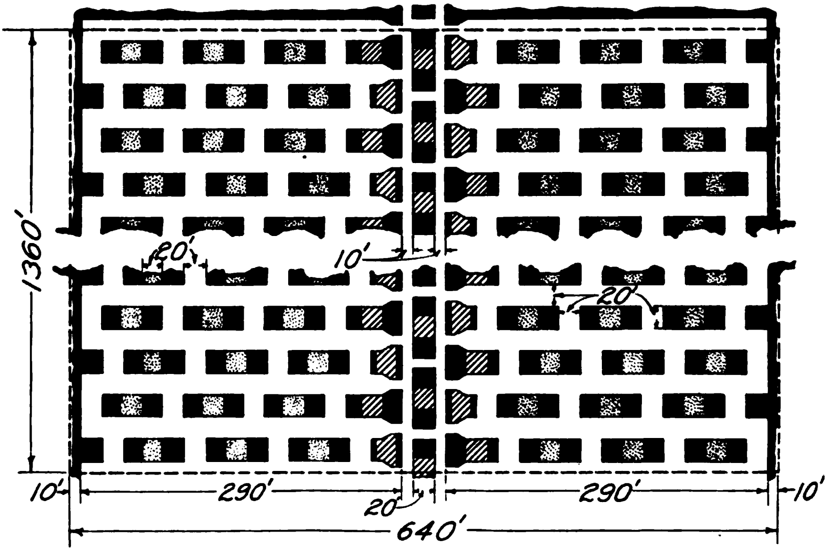

FIG. 19. DIMENSIONS OF ROOMS AND CROSS ENTRIES AT DEWMAINE

sidered is 640 feet wide by 1360 feet long and has an area of 870,000 square feet.

The following notes give the results of experience with different dimensions of rooms and the extraction of different amounts of pillar coal. With each of the two pillar widths different amounts of coal were extracted. With rooms 20 feet wide on 40-foot centers, plan No. 1, shown in white, gave the following extractions:

		Square feet
Rooms		68×5725=389,300
Cross-cuts		4×68× 400=108,800
Entries		2×10×1360= 27,200
Entry cross-cuts		21× 200= 4,200
Total area excavated	(60.7 per cent)	529,500

The experience of the company thus far indicates that workings with these dimensions will stand indefinitely except where soft mud or quicksand predominates in the cover.

Plan No. 2 involves the driving of additional cross-cuts in the room pillars after the room has been completed. These additional cross-cuts are shown by the dotted areas in the figure. The additional area extracted is:

3×68×400=81,600 square feet

Total area excavated . . . . (70.2 per cent) 611,100

Experience indicates that squeezing will occur in rooms, but that the entry stumps will protect the entry so that it will not be closed. More or less water will follow the squeeze. The surface will subside gently to a depth of 2 feet to 4 feet in the center of the area.

Plan No. 3 involves the driving of additional cross-cuts in the room stumps and chain pillar, while retreating, as shown by the hatched areas. The additional area excavated is:

		Square feet
Room cross-cuts		68 feet×400 feet= 27,200
Entry cross-cuts		20 feet×400 feet= 8,000
Total area excavated	(72.4 per cent)	646,300

The results, as far as subsidences are concerned, are practically the same as those obtained by following plan No. 2, except that the entry is closed by the squeeze and more water enters the mine. The surface subsidence is practically the same as in plan No. 2.

Plans Nos. 4, 5, and 6 apply to the same method of working, but with room pillars only 14 feet wide which make 80 rooms in a block 640 feet by 1360 feet.

Plan No. 4 involves excavation of the following areas:

	Square feet
Rooms	80×5725=458,000
Room cross-cuts	80×4×280= 89,600
Entries	2×10×1360= 27,200
Entry cross-cuts	21×200= 4,200
Total area excavated	(66.5 per cent) 579,000

When this plan is followed, squeezing occurs in a room a few months after the first working and more or less water enters the mine. The surface subsidence is about the same as in plan No. 2.

Plan No. 5 involves the driving of additional cross-cuts, as in plan No. 2, and the additional area excavated is:

	Square feet
Cross-cuts	3×80×280=67,200
Total area excavated	(74.2 per cent) 646,200

The results are practically the same as those obtained by following plan No. 2, except that more water enters the mine and the subsidence of the surface is deeper.

When additional cross-cuts are driven in room and entry retreating, as shown by the hatched areas, in plan No. 6, the additional areas excavated are:

	Square feet
Room cross-cuts	80 feet×280 feet=22,400
Entry cross-cuts	20 feet×400 feet= 8,000
Total area excavated	(77.7 per cent) 676,600

In this case the entire area squeezes, and a large quantity of water enters the mine. The surface subsidence extends over the whole area and is greater than with any of the other plans.

In the Dewmaine fields it has not been found practical to apply any plan except No. 1 until a considerable portion of the mine is ready for abandonment. Slight changes in the projection, however, are made when changes in physical conditions make them advisable. Rooms are driven 20 feet wide, but pillars are sometimes reduced to 18 feet and entries are made either 10 or 12 feet wide.

In this field a great deal of trouble has been caused by the entry of water whenever the extraction of too much coal disturbed the overlying strata. Since plan No. 1 alone permits the indefinite sustaining of the overlying material, it is the only one which can be followed without entailing a great expense for handling water. Extraction is therefore limited to about 60 per cent of the panels or blocks, and must be considerably less when considering the whole mine. The calculated percentages of extraction given on page 34 for rooms and pillars of the same ratio of width,— namely, 25-foot rooms with 25-foot pillars, indicate that the total extraction is about 10 per cent less than the extraction in the panel area. It is therefore probable that the total amount of coal extracted in the mine as a whole is about 50 per cent. At various times plans No. 2 and No. 3 have been tried in limited areas, but trouble has always been caused by squeezes and inflow of water.

At the present time mining at No. 8 has proceeded far enough to permit the application of plan No. 3 in working from the boundary toward the shaft. The additional recovery will probably make the total extraction for the entire mine about 60 per cent.

Mr. Lyman points out that both the depth of cover and the nature of the ground vary considerably within short distances in the district referred to and that different results might be obtained within a short distance of the mine mentioned.

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APPENDIX III

WORK OF J. C. GIBSON

J. C. Gibson of the Standard Engineering Company of Duquoin has developed a method for calculating the percentage of extraction and the future life of a mine by which it is possible to indicate the parts of the workings in which the losses occur. The following description of procedure is published through the courtesy of Mr. Gibson.

When this method is applied, a tracing of the workings is made showing the outlines of groups of rooms, entries, barrier pillars, and lost areas. In the tracing these separate portions are given distinctive colors in order to prevent any possible confusion. Each area is then measured. This measurement can best be done with a planimeter, but very close approximation to the correct areas can be attained by measuring with a scale, especially if the outlines are not very irregular.

The application of this method to a part of a mine is shown in Fig. 20. The sums of the areas of the different portions in the entire mine are as follows:

Areas worked out	*(Acres)*	*Percentage of Total Area*
Rooms and pillars	157.16	59.76
Entries	62.40	23.73
Lost coal	3.44	1.30
Barriers	40.00	15.21
Total area covered by workings, with exception of the shaft pillar	263.00	100.00

	Tons
Room coal produced	1,421,023
Entry coal produced	378,744
Total coal produced, not including coal taken from the shaft pillar in driving the bottom	1,799,767

The tonnage produced from entries was calculated from the length, width and height of the entries and the weight of the coal per cubic foot, a method permissible when entries are driven with

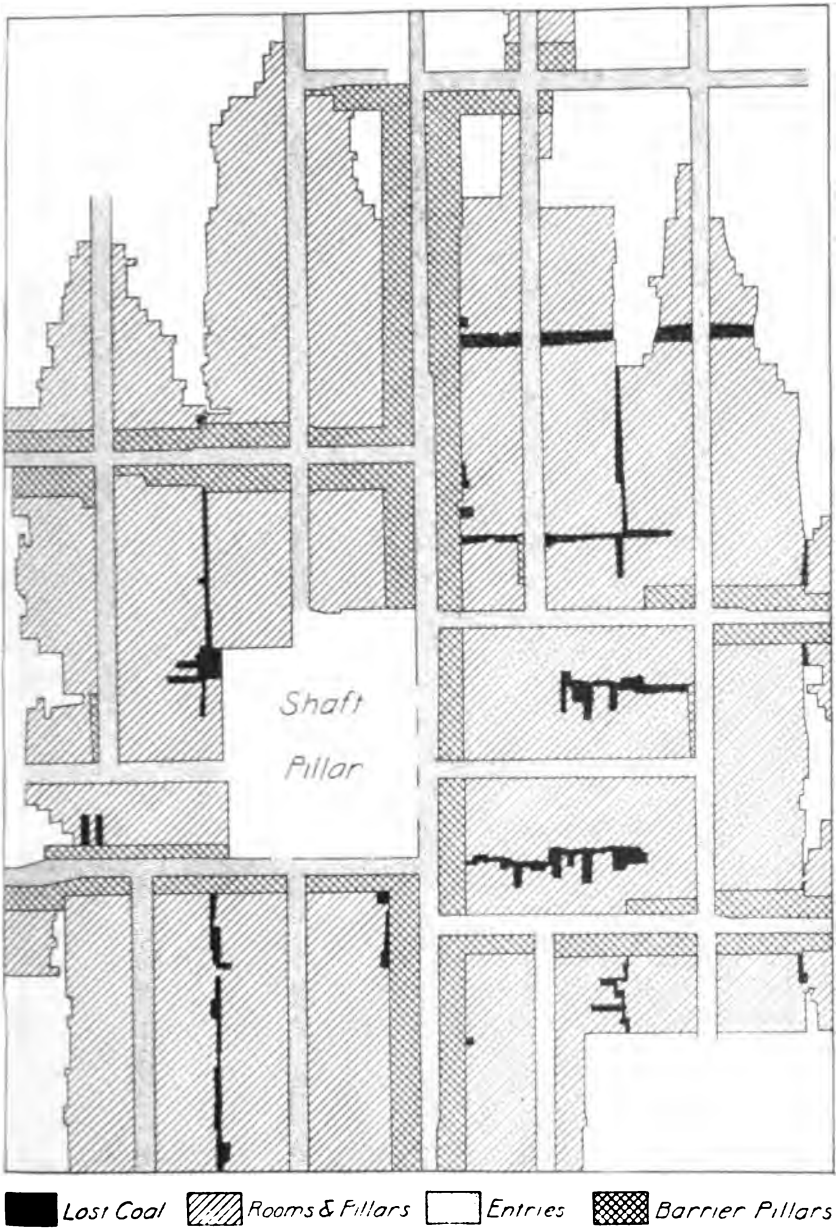

FIG. 20. PORTION OF MINE AS MAPPED BY J. C. GIBSON

careful adherence to the projected dimensions. The tonnage produced from other workings is the difference between total output and entry coal.

The average thickness of coal being 9.4 feet and the weight per cubic foot 81.25 pounds, the amount of coal originally present per acre was

$$\frac{43{,}560 \times 9.4 \times 81.25}{2{,}000} = 16{,}634 \text{ tons}$$

The area worked over by rooms and pillars is 157.16 acres. The coal originally present in the room and pillar area was 157.16 × 16,634 = 2,614,199 tons; and the percentage of extraction in the territory occupied by rooms and pillars was

$$\frac{1{,}421{,}023 \times 100}{2{,}614{,}199} = 54.36 \text{ per cent}$$

The entries occupied 62.40 acres, and the coal originally present was 62.40 × 16,634 = 1,037,961 tons. The percentage of extraction in territory occupied by entries was

$$\frac{378{,}744 \times 100}{1{,}037{,}961} = 36.49 \text{ per cent}$$

The coal originally present in the whole area was 263 × 16,634 = 4,374,742 tons and the percentage of extraction over the whole area worked out was

$$\frac{1{,}799{,}767 \times 100}{4{,}374{,}742} = 41.14 \text{ per cent}$$

Since the thickness of the bed is 9.4 feet and the height of entries only 7 feet, the percentage of area excavated in entries is $\frac{9.4}{7}$ of the percentage of coal extracted.

$$\frac{9.4}{7} \times 36.49 \text{ per cent} = 49.00 \text{ per cent}$$

The data given do not provide a basis for the calculation of percentage of area worked out in the room-and-pillar blocks, because some of the top coal was taken. If no top coal had been taken, the percentage of area worked out in the seven feet of coal being mined would be equal to the percentage of coal produced from that seven feet. The amount of coal originally present in the areas occupied by rooms and pillars in a thickness of seven feet was

$$\frac{43{,}560 \times 7 \times 81.25 \times 157.16}{2000} = 1{,}946{,}799 \text{ tons}$$

As the coal taken out from these areas was 1,421,023 tons, the percentage of area excavated would have been 73.0 per cent if a thickness of only seven feet had been worked.

$$\frac{1{,}421{,}023 \times 100}{1{,}946{,}799} = 73.0 \text{ per cent}$$

If all the top coal had been taken down to a height of 9.4 feet, the percentage of area worked out would be the same as the percentage of coal produced when the thickness of 9.4 feet is considered, —that is, 54.36 per cent. Since some top coal was left, the percentage of area worked out must have been greater than 54.36 per cent and less than 72.2 per cent in order to give this percentage of extraction; however there are no data from which accurately to calculate the percentage.

In some mines where the only "solid" coal produced is top coal, all the remainder being known as "machine" coal, it would be possible to get from the books of the coal company the number of tons of solid coal paid for,—that is, the top coal. Then the percentage of area worked out in rooms could be determined from the tonnage produced.

It is claimed by Mr. Gibson that given the data on a number of mines in the preceding form, comparisons may be made and possibly much valuable information obtained. For example, mines in which a high percentage of extraction had been obtained in the room-and-pillar areas would indicate the practice to be followed in planning a new operation, provided, of course, that the history of those mines showed their practice to be satisfactory; mines in which the smallest percentage of coal had been lost in barrier pillars, provided the barriers had proved sufficient, would indicate the dimensions of barriers for use in new operations; and mines having the smallest ratio of entry area to room area would suggest efficient methods of developing a property.

Thus, from a number of plans of actual operations, might be developed a composite plan more efficient than any of those studied. It is evident that the two sets of percentages, those of the entire coal seam and those of the number of feet of the seam worked, will enable comparisons to be made with most of the properties studied.

PUBLICATIONS OF THE ILLINOIS COAL MINING INVESTIGATIONS

Bulletin 1. Preliminary Report on Organization and Method of Investigations. 1913. *None available.*

Bulletin 2. Coal Mining Practice in District VIII (Danville), by S. O. Andros. 1913. *None available.*

Bulletin 3. Chemical Study of Illinois Coals, by S. W. Parr. 1916. *Twenty-five cents.*

Bulletin 4. Coal Mining Practice in District VII (Mines in bed 6 in Bond, Clinton, Christian, Macoupin, Madison, Marion, Montgomery, Moultrie, Perry, Randolph, St. Clair, Sangamon, Shelby, and Washington counties), by S. O. Andros. 1914. *Free upon request.*

Bulletin 5. Coal Mining Practice in District I (Longwall), by S. O. Andros. 1914. *None available.*

Bulletin 6. Coal Mining Practice in District V (Mines in bed 5 in Saline and Gallatin counties), by S. O. Andros. 1914. *Free upon request.*

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Bulletin 11. Coal Resources of District VII (Counties listed in Bulletin 4), by Fred H. Kay. 1915. *None available.*

Bulletin 12. Coal Mining Practice in District IV (Mines in bed 5 in Cass, DeWitt, Fulton, Knox, Logan, Macon, Mason, McLean, Menard, Peoria, Sangamon, Schuyler, Tazewell, and Woodford counties), by S. O. Andros. 1915. *Free upon request.*

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Bulletin 100. Engineering Experiment Station, University of Illinois, The Percentage of Extraction of Bituminous Coal, with Special Reference to Illinois Conditions, by C. M. Young. 1917. *Free upon request.*

Bulletin 113. Engineering Experiment Station, University of Illinois, Panel System of Coal Mining, A Graphical Study of Percentages of Extraction, by C. M. Young. 1919. *Free upon request.*

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CORONA DISCHARGE

BY
EARLE H. WARNER
WITH
JAKOB KUNZ

BULLETIN No. 114

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BULLETIN No. 114 JUNE, 1919

CORONA DISCHARGE

BY

EARLE H. WARNER

INSTRUCTOR IN PHYSICS

WITH

JAKOB KUNZ

ASSOCIATE PROFESSOR OF PHYSICS

ENGINEERING EXPERIMENT STATION
PUBLISHED BY THE UNIVERSITY OF ILLINOIS, URBANA

R. R.

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CORONA DISCHARGE

CHAPTER I

INTRODUCTION

1. *Statement of the Phenomenon.*—When high potential differences exist between conductors, the insulating property of the surrounding air partially breaks down, and a conduction of electricity through the air takes place, usually accompanied by a glow at either one of the conductors or in the intervening space. This glow is called the corona. The phenomenon is commonly seen when static machines or Tesla coils are operated in the dark, and less frequently from the tips of lightning rods during an electric storm. The corona is evident at night as it surrounds very high voltage alternating current transmission lines. The conduction represents a loss of power, which on long lines may become an important item. Peek (1), Whitehead (2), and others (3) have carefully studied this phenomenon for alternating differences of potential. In 1912, Peek (4), by a stroboscopic method, showed that there is a difference between the corona discharge from positive and negative conductors. This difference shows that corona caused by alternating potentials is a combination of two effects; and in order to study these effects separately and thus to learn the true facts concerning the phenomenon, continuous potentials must be used. A study of the corona caused by continuous potentials may produce engineering data of value owing to the increasing development of high tension direct-current generation and transmission. Previous to 1914, Watson (5) and Schaffers (6) were the only men who had experimented on the direct current corona.

Because of the desirability of a greater knowledge of the direct current corona, the Physics and Electrical Engineering Departments of the University of Illinois determined to carry out detailed research to develop a satisfactory theory for the corona phenomena. It is the purpose of this bulletin to present the results of the research which has been completed during the last few years.

Note.—The numbers within parentheses refer to the bibliography, page 131.

2. *Acknowledgments.*—The writers desire it to be clearly understood that the research presented in this bulletin is a compilation of the work done by the following, **Farwell**, **Crooker**, **Davis**, **Breese**, **Owens**, **Anderegg**, **Faulkner**, and **Warner**, under the direction of **Jakob Kunz**. The work of these men, as recorded in theses or in published articles, forms the basis of this bulletin. In many instances in order that statements might be accurate the words of the authors have been copied directly.

3. *Apparatus.*—The continuous voltage used in these investigations was obtained by means of a battery of forty, 500-volt, 250-watt, continuous-current, shunt-wound generators connected in series.

These machines are divided into two sets of ten machines each, and one set of twenty machines, each set being driven by a belt-connected, continuous-current shunt motor. The generators are mounted on insulating bases and the shafts of the separate machines are connected by insulating couplings. One terminal of each machine is permanently connected to its own frame in order definitely to limit the electrical strain on the machine insulation to the voltage generated by one armature.

The field of each generator is connected directly across the armature terminals, a single pole knife switch being included in the circuit in order that the machine may either be made to generate or to run idle at will. These switches were operated by means of a hard rubber rod approximately eighteen inches in length, since they may be twenty thousand volts above earth potential. The generators were run somewhat below rated speed in order to limit, to a safe value, the voltage generated without external resistance in the field circuit. The voltage of the machine supplying current to the driving motors was maintained at a constant value by means of a voltage regulator. The constant speed of the driving motors thus produced caused the resultant high potential of the battery of generators to be practically constant. A fine adjustment of voltage was obtained by means of a rheostat in the field circuit of one of the generators. Fig. 1 is a general view of the generating plant.

Most of the experimenters working in this field have dealt with corona in air. Air, however, changes in chemical composition immediately upon the formation of the corona, so that if accurate data are desired within the corona discharge region some arrangement

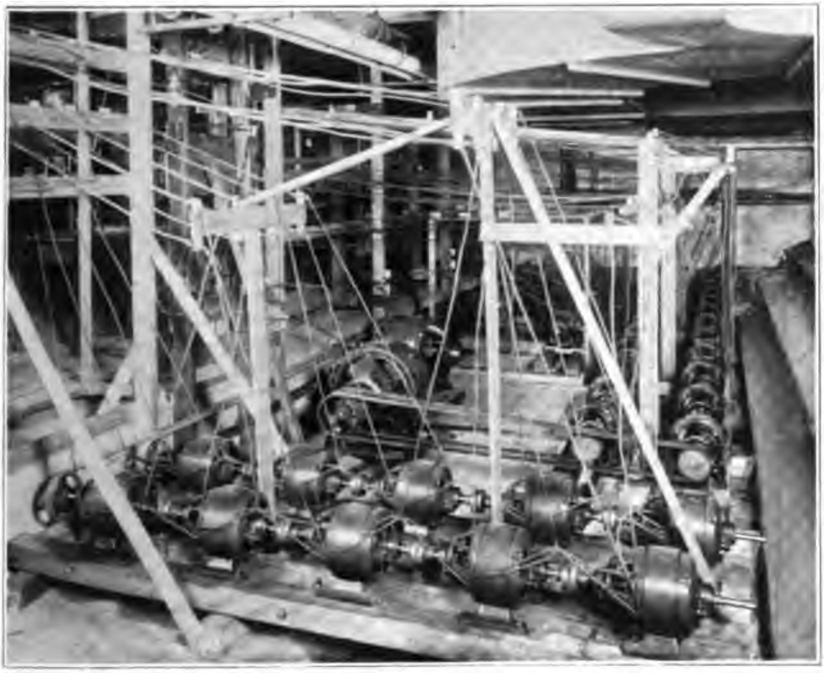


FIG. 1. GENERAL VIEW OF GENERATING PLANT

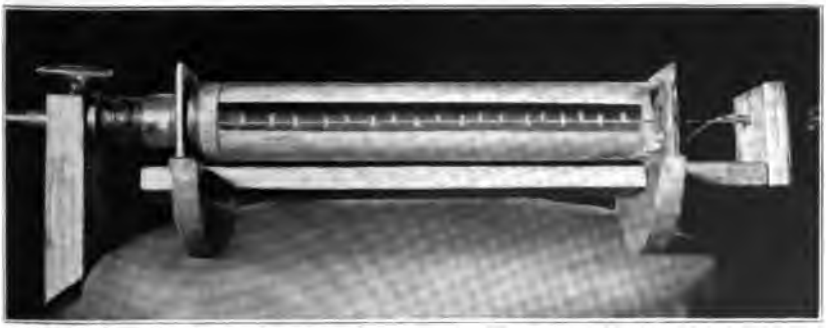


FIG. 2. A TYPICAL TUBE, WITH SLOT

must be made to insure uniformity of chemical structure in the dielectric at all times. Such uniformity is often accomplished by replacing the gas immediately surrounding the conductors as fast as its composition changes. This renewal is often impracticable.

To add to the knowledge of the corona in a substance which probably does not change chemically, experiments have been performed with chemically pure hydrogen as the dielectric. The hydrogen used in this part of the work was produced by the action of hydrone, a commercial alloy of lead and sodium, upon water. The reaction of the sodium with the water produces hydrogen, the lead acting as a retarding agent only. The hydrogen was collected over water and purified as used.

The purifying process consisted in forcing the hydrogen through concentrated sulphuric acid drying bottles placed in series with a calcium chloride tube, and then through a tube in a combustion furnace which contained red hot metallic calcium. The drying agents removed all water vapor and the heated calcium removed all traces of oxygen and nitrogen. Immediately after purification the hydrogen was conducted into the corona apparatus. In the purification of the hydrogen a discharge tube was connected directly to the corona apparatus, and the purity of the hydrogen was tested with a Hilger spectroscope. After careful purification no traces of any other gas than hydrogen were visible in the bright line spectrum.

The type of the corona discharge tube, used in most of the experiments to be described, was a cylinder with a wire strung along its axis. This type of tube was chosen for several reasons:

(1) The corona phenomena, occurring when this type of apparatus is used, lend themselves peculiarly well to mathematical analysis.

(2) The construction, manipulation, operation, and repair of the apparatus are extremely simple.

(3) The field distribution is symmetrical with respect to the wire, and any irregularities in the wire are immediately recognizable in the discharge.

(4) This type of apparatus has been used by other investigators; thus results could be compared with greater assurance of reliability.

The apparatus was so arranged that wires of different sizes could be easily strung and held taut exactly along the axis of the cylinder. In order to limit the length of the wire from which the discharge took place, glass plates with holes for the wire to pass through were sealed to the ends of the cylinder so that the holes were on the axis of the cylinder and metal bushings were inserted in these holes. The wire which was run through the bushings was held taut by sealing wax. The cylinder was provided with a side tube through which the air could be pumped out and dry air or pure gases allowed to enter. When the visible character of the corona was to be studied and photographed, the metal cylinder was provided with a longitudinal slot and the whole tube placed in a glass cylinder. Fig. 2 shows a typical tube with slot.

The voltages, if low, were measured with a Braun type Kohl electrostatic voltmeter, and, if higher, a vertical type Kelvin electrostatic voltmeter, having ranges of 5,000, 10,000, and 20,000 volts, was used. Frequently these instruments were calibrated by means of an attracted disk electrometer. In computing the voltages from the disk electrometer the end correction as treated by Maxwell (7) was applied.

Currents were measured by means of a d'Arsonval galvanometer and an Ayrton universal shunt. These were calibrated as a unit by connecting them in series with a high resistance and a dry cell, the

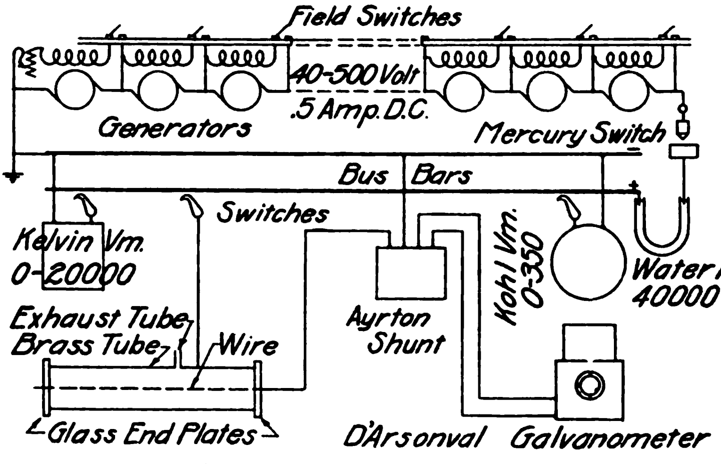


FIG. 3. DIAGRAM OF CONNECTIONS

voltage of which had previously been determined by means of a potentiometer. The voltage of the dry cell was determined both in open circuit and on closed circuit with the smallest series resistance used in the calibration placed in series with the cell. The change in terminal voltage due to the current flowing was, in every case, found to be entirely negligible.

The machines, measuring instruments, and corona apparatus were connected as is shown in Fig. 3. The arrangement of the connections made so that the corona occurs between a positive wire and a grounded coaxial cylinder will be referred to throughout this bulletin as corona with "the wire positive" or as "positive corona." Likewise, when the connections are such that the corona occurs between a positive tube and a grounded wire (as in Fig. 3), the corona will be referred to as corona with "the wire negative" or as "negative corona."

CHAPTER II

General Appearance of the Corona about a Wire in a Cylinder

As the voltage across the corona apparatus is gradually raised, a point is reached when a marked increase in the current occurs, and a further increase in voltage causes the current to increase very rapidly. The voltage at which this sudden increase, indicated by the deflection of the galvanometer, occurs is called the "critical voltage." "Visible glow voltage" means the voltage at which the light about the wire first appears. The visible glow voltage may be identical with, or higher than, the critical voltage.

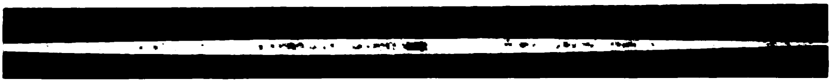
The positive and negative corona have entirely different appearances and will be considered separately.

4. *Wire Positive in Air.*—For all pressures and sizes of wire used a uniform purple glow surrounds the positive wire. The wire has a tendency to vibrate at high pressures and high current densities as is shown by *a*, Fig. 4. The thickness of the luminous film seems to be a constant for all current densities and pressures, the intensity or brilliance of the discharge only varying with the current and pressure. Positive corona in air at various pressures is shown in Fig. 4.

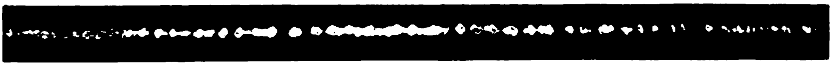
5. *Wire Negative in Air.*—With the wire negative the appearance of the corona is changed in a very marked degree as is shown in Figs. 4 and 5. From these photographs the following properties can be observed:

(1) With a constant wire diameter and decreasing pressures the discharge gradually changes from a fairly uniform luminous mass with ragged boundaries to a beady discharge as is shown in Fig. 5. The luminous mass is shown breaking up into beads at *f* and *g*, Fig. 4.

(2) For a constant pressure and decreasing wire radii the fairly uniform luminous discharge gradually changes to the beady discharge, so that for small wires (less than 0.17 mm. in diameter) the beady discharge occurs at all pressures between



(*a*) Wire +, Pressure 747 mm., Volts 9110, Amperes 11.8×10^{-5}

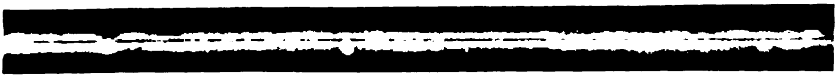


(*b*) Wire —, Pressure 747 mm., Volts 8850, Amperes 12.0×10^{-5}

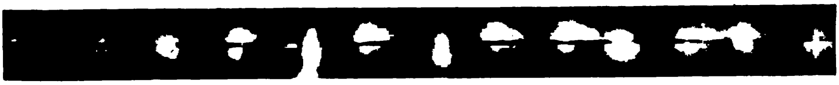
(*c*) Wire +, Pressure 427.0 mm., Volts 6795, Amperes 6.60×10^{-3}

(*d*) Wire —, Pressure 427.0 mm., Volts 6350, Amperes 7.11×10^{-3}

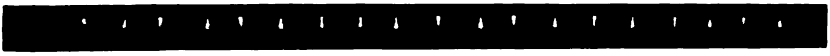
(*e*) Wire +, Pressure 229.0 mm., Volts 4680, Amperes 6.72×10^{-3}



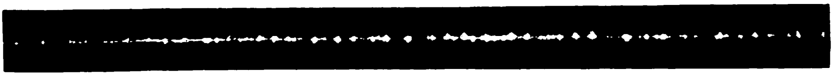
(*f*) Wire —, Pressure 229.0 mm., Volts 4265, Amperes 6.60×10^{-3}



(*g* Wire —, Pressure 87.0 mm., Volts 2200, Amperes 6.70×10^{-3}



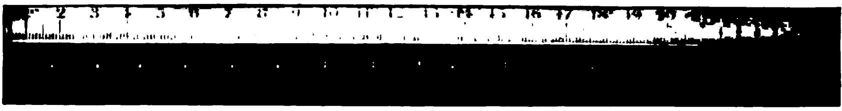
(*h*) Wire —, Pressure 46.9 mm., Volts 1450, Amperes 4.33×10^{-4}



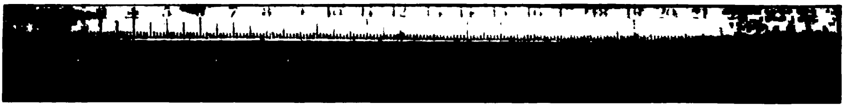
(*i*) A. C., Pressure 747 mm., Volts 8180, Amperes 6.65×10^{-5}

Fig. 4. Visual Characteristics of the Corona in Air

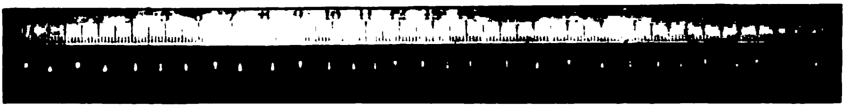
(a) Wire—, Pressure 119.3 mm., Volts 2500, Amperes 0.327×10^{-4}



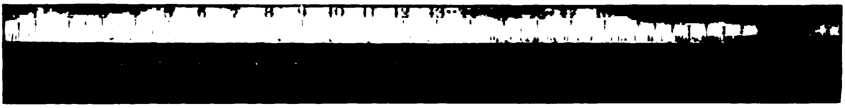
(b) Wire—, Pressure 119.3 mm., Volts 2800, Amperes 1.03×10^{-4}



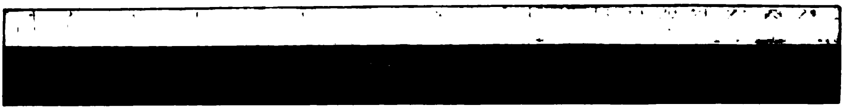
(c) Wire—, Pressure 119.3 mm., Volts 3160, Amperes 2.23×10^{-4}



(d) Wire— Pressure 119.6 mm., Volts 3550, Amperes 4.65×10^{-4}

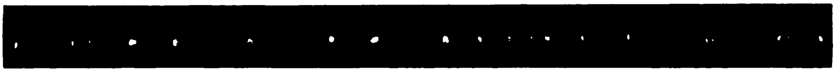


(e) Wire—, Pressure 119.6 mm., Volts 3870, Amperes 10.0×10^{-4}



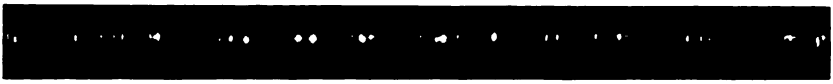
(f) Wire—, Pressure 119.6 mm., Volts 4020, Amperes 16.2×10^{-4}

Fig. 5. Variation of the Number of Beads with the Potential Difference

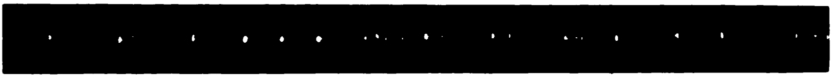


(*a*) Wire —, Pressure 778.0 mm., Volts 3721, Amperes 9.15×10^{-3}

(*b*) Wire +, Pressure 436.0 mm., Volts 3840, Amperes 15.0×10^{-5}

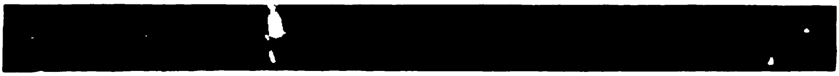


(*c*) Wire —, Pressure 436.0 mm., Volts 2390, Amperes 18.0×10^{-3}



(*d*) A. C. Pressure 436.0 mm., Volts 2710, Amperes 18.3×10^{-3}

(*e*) Wire —, Pressure 391.0 mm., Volts 4585, Amperes 3.57×10^{-3}



(*f*) Wire +, Pressure 234.5 mm., Volts 4500, Amperes 21.3×10^{-5}

(*g*) Wire —, Pressure 234.5 mm., Volts 2025, Amperes 1.76×10^{-3}

Fig. 6. Corona in Hydrogen

atmospheric and 50 mm. of mercury. Under certain conditions of pressure and voltage these negative beads or brushes distribute themselves uniformly along the wire as is shown in Fig. 5. For the lowest pressures the beads consist of a bright cylindrical core along the wire, this core being surrounded by a narrow dark space and enveloped in turn by a purple glow of relatively large diameter. For increasing pressures the central core contracts to a point on the wire, from which the discharge spreads out fanlike in a plane at right angles to the wire. For still higher pressures the fan seems to close and finally to degenerate to a small brush.

(3) The number of brushes varies with the potential difference. That the number of brushes is a function of the potential difference is shown in Fig 5. Between the voltages at which the arrangement of the brushes was most regular, there seemed to be a transition period in which there were many little brushes in addition to those that were larger. An increase of voltage would then produce a set of full-sized brushes.

6. *Wire Positive in Hydrogen.*—With the wire positive and sizes of wire less than 0.405 mm. in diameter, the wire is surrounded by a thin luminous layer which is essentially uniform, as shown at *b*, Fig. 6. As the size of the wire is increased, this glow becomes more and more irregular. At first there are spots somewhat brighter than others. For a wire as large as 2.59 mm. the discharge takes the form of a large number of brushes similar to the point-discharge in air. It has been impossible to obtain satisfactory photographs of these brushes. They are closely spaced along the length of the wire with a fairly uniform glow between them. The positive discharge is blue in color. If the potential is increased to a high value, a brilliant red spark will pass between the wire and the tube. This spark is followed by a pale blue arc having incandescent blue spots at both ends. These arcs are illustrated in *f*, Fig. 6.

7. *Wire Negative in Hydrogen.*—The typical form of discharge with the wire negative is shown in Fig. 6. For small wires and large pressures the discharge on the wire consists of distinct bright beads with well defined edges, while for large wires and small pressures it changes to a more fuzzy discontinuous discharge. As the potential

is continually increased from values below to values above the critical point, the first evidence of a breakdown of the gas around the wires of small radii is the appearance of an intermittent flickering glow which changes almost immediately with the change of potential to a number of flickering unstable bright spots on the wire. For wires larger than 0.200 mm. in diameter the flickering glow does not form, but the beady discharge is the first to form for these wires. In all cases, however, a voltage increase causes an increase in the number of spots; the corona current gradually increases (a time element enters in the building up of the current) and finally a stage is reached where the spots condense into one brilliant bead. The formation of this bead is accompanied by an extremely rapid increase of current and a correspondingly large and rapid drop in the potential across the tube. A further increase in voltage causes more small bright spots to form, and also causes an increase in the brilliancy of the bead. The newly formed spots condense into a second bead upon a further increase in voltage, and in this manner the number of beads and the current increase as the tube voltage is increased.

If the generator voltage is now decreased, the behavior of the corona is somewhat different. If there are nine beads upon the wire, for example, they will persist but become less and less brilliant until they finally collapse into one or two beads. It seems, therefore, that with increasing voltage the beads appear one by one until the maximum voltage is reached, when the number of beads is also a maximum; but that with decreasing voltage the beads remain on the wire at much lower voltages than those at which they were formed. In fact they persist until a change in number takes place when, not only one but several beads disappear, so that the beads remaining again increase in brilliance, and a considerable lowering of the voltage is necessary to destroy more beads. With a constant number of beads the current increases with increasing voltage. The bead brilliancy increases also with an increase of current. With a change in the number of beads the current value makes a sudden change. This change is approximately proportional to the change in the number of beads.

Opposite each bead for practically all pressures and all sizes of wire used, there is a number of bright spots on the tube. The number of spots varies from ten to twelve for small wires and for small pressures to many hundred for large wires and for large pressures.

For a given wire and a given pressure the number of spots depends upon the magnitude of the corona current. If only a few spots exist, they will be grouped together around the side of the bead nearest the tube, but when the current is large the spots will form a band extending entirely around the tube and of a width of one centimeter or less. These spots vary in color from pale yellow to a milky blue, depending on the pressure, current, and size of wire. With low pressures and large currents these spots may appear as brilliant green fans with yellow spots where they touch the tube. The green color may be due to the brass tube and not to an inherent property of the hydrogen. The presence of these spots at the tube surface seems to indicate an ionizing gradient in this region.

The predominating color of the various discharges through hydrogen is blue, which ranges from a light silver blue to sky blue. The exceptions to this characteristic blue color have been mentioned in the preceding paragraph.

8. *Alternating Current Corona in Air and Hydrogen.*—When an alternating voltage is impressed across a tube filled with air, the discharge seems to be a combination of the discharges with the wire positive and with the wire negative. As would be expected, the beads appear during the half cycle when the wire is negative and the uniform glow appears during the half cycle when the wire is positive. This is shown in *i,* Fig. 4.

When alternating current is applied to a tube filled with hydrogen, the discharge always appears to be very similar to that observed when the wire is negative, as shown clearly in *d,* Fig. 6. The absence of the uniform luminous layer between the beads shows that the characteristic positive discharge is absent; thus either partial or perfect rectification is indicated. The absence of the positive discharge can better be understood after studying the starting points of the positive and negative corona, as shown in the curves which follow.

If the alternating voltage is sufficiently increased the positive corona discharge forms, and finally with a sufficient increase the positive arc is produced. That the arc occurs during the half cycle in which the wire is positive can be verified by two methods. (1) By watching the discharge as the voltage is increased to the arcing value, one observes the first arc to be a reddish color. This is known to be the positive arc. (2) Oscillograms show that the change in current, indicating the start of the arc, occurs from a positive current lobe.

CHAPTER III

THE STARTING POINT OF THE CORONA

For engineering purposes it is important to know the factors which affect the starting point of the visible glow. In air, of a given humidity, the starting point* is mainly a function of two variables: (1) the radius of the wire, (2) the pressure of the air. In hydrogen the first few investigations disclosed the fact that the starting voltages were erratic under apparently similar temperature, pressure, and wire surface conditions. All disturbing elements, except possibly a time element, seemed to be eliminated; so tests were made to determine the effect on the starting voltage of a variation in the length of time elapsing between successive readings. Fig. 7 shows the results of a repre-

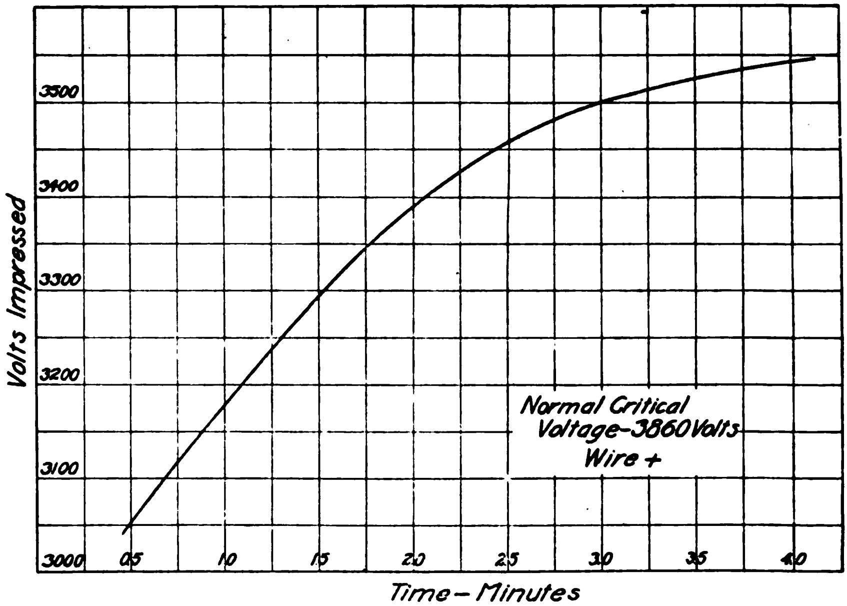


FIG. 7. VARIATION OF CRITICAL VOLTAGE WITH TIME INTERVAL BETWEEN OPENING AND RECLOSING THE CIRCUIT

sentative test of this type. The method of procedure for taking the readings for this test was as follows: The circuit was closed, corona was started, and the voltage was increased to a value sufficient to make the current reading 2.472×10^{-4} amperes. The circuit was then opened, and the time of opening the circuit was called zero time. One-half minute later the circuit was closed and the critical voltage value was determined as soon as possible. After this determination was made, the current was again brought to 2.472×10^{-4} amperes, the circuit opened and the new time was called zero time. A critical voltage determination was made one minute later. This process was continued until a definite conclusion concerning the variation of critical voltage with time was reached. As a direct consequence of this test all determinations of critical voltages in hydrogen were made only when enough time had elapsed after breaking the corona circuit to insure a resumption of normal conditions.

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*The influence of humidity and temperature upon the starting point will be discussed in Chapter V.

Experiments were also conducted to determine whether or not the starting voltage was different for the two following cases: (1) when the voltage was gradually increased in value until the critical value was reached, and (2) when the full voltage was suddenly thrown across the tube. No appreciable difference was found.

In addition to this time element the starting point of the visible glow in hydrogen also depends upon the radius of the wire and the pressure of the gas. In the next two sections the variations of the glow voltage with these factors are discussed.

9. *Glow Volts—Radius Curves.*—Fig. 8 gives curves showing the variation of the glow voltages with the radius of the wire when air and hydrogen formed the dielectric. In the air curves the data for points representing wires of very small radii were taken from voltage-ampere curves for silver and tungsten wires. The data for the rest of the points were taken from the characteristic voltage-ampere curves for copper as reproduced in this bulletin. The silver wire used was really silver wire with a platinum core, known as "Wollaston wire." It was used both in its original state, diameter 0.0517 mm., and with some of the silver dissolved off; thus the wires used were of average diameters 0.027 and 0.037 mm. The tungsten wire was that used in 25-watt lamps. The diameters of the very small wires were obtained by the use of a microscope fitted with a stage ruled with parallel lines.

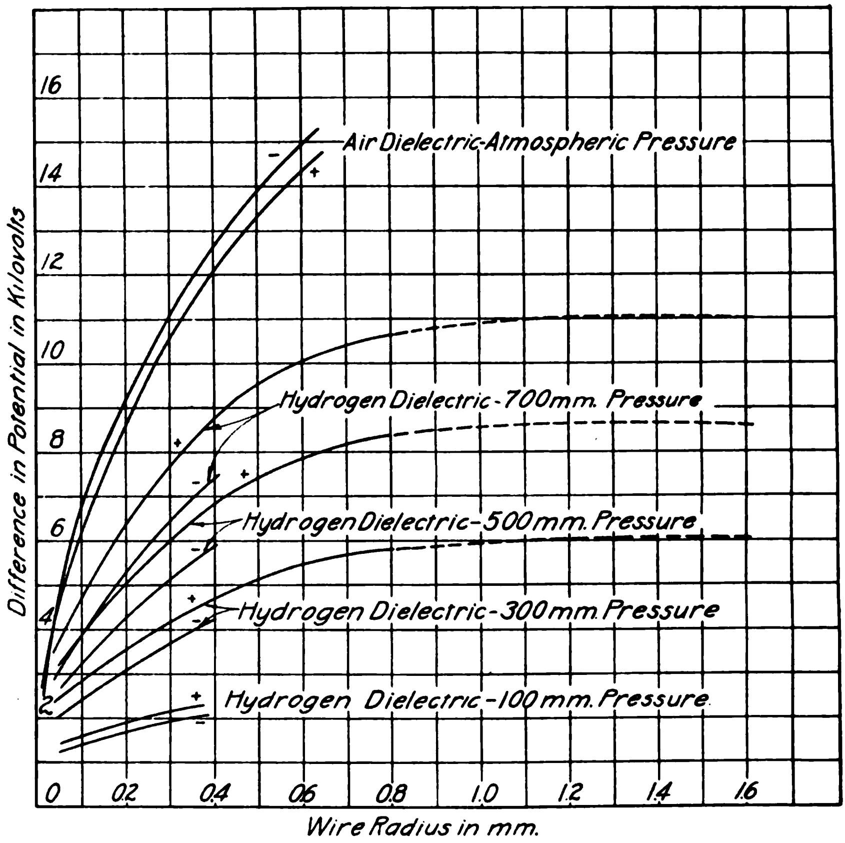

FIG. 8. VARIATION OF THE GLOW VOLTAGES WITH THE RADIUS OF THE WIRE

From the air curves the following conclusions can be drawn:

(1) For the smaller wires, the negative glow appears before the positive.

(2) For the larger wires, the positive glow appears before the negative.

(3) The diameter of wire, 0.075 mm., serves as a dividing line between these two groups. Shaffers has noted similar data which when plotted show a crossing of the curves for the starting points of the positive and negative corona, but he gives 0.01 cm. as the wire radius to separate the two groups. He does

not specify what he considered as the starting point of the negative corona, and it is accordingly not practical to compare his value with that shown in the air curves.

The hydrogen curves show: (1) that the critical voltage for hydrogen is very much less than that for air, (2) that for any particular size of wire and any given pressure the negative starting voltage is much less than the positive voltage. It is seen that for most of the range of wires used the opposite is true for air.

10. *Glow Volts—Pressure Curves.*—Fig. 9 gives curves showing the variation of critical voltages with the pressure. In these experiments only one wire was used when the tube was filled with air but each of two wires was successively used when the tube was filled with hydrogen.

These curves show that in both air and hydrogen for a single size of wire, an increase in the gas pressure requires an increase in the voltage necessary to start the corona discharge. These curves also

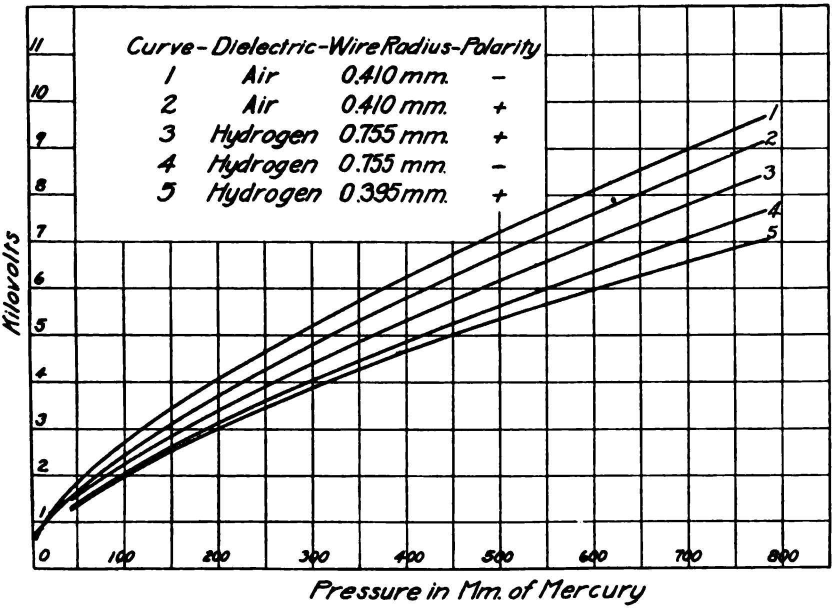

FIG. 9. VARIATION OF THE GLOW VOLTAGES WITH THE GAS PRESSURE

show: (1) that the positive critical voltage for air is lower than the negative critical voltage, while for hydrogen the negative critical voltage is the less; (2) that for a constant pressure and size of wire the critical voltage in hydrogen is much lower than the critical voltage in air.

11. *Starting Point Expressed in Terms of Electric Intensity as a Function of Radius and Pressure.*—The electric intensity, ϵ, at the surface of the wire, subject to a potential, V, coaxial with a cylinder at zero potential, is given by the following equation:

$$\epsilon = \frac{V}{a \log_e \frac{b}{a}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where a = radius of the wire,
b = radius of the cylinder.

Thus if V, a, and b are known, ϵ can be computed. A sample table showing glow voltage and computed electric intensity as a function of the radius of the wire in air is given in Table 1. While with increasing radius the glow voltage increases, the electric intensity, ϵ, at the surface of the wire decreases. Fig. 10 shows this relation graphically.

TABLE 1

CRITICAL DIFFERENCE OF POTENTIAL TO CAUSE CONTINUOUS GLOW AS FUNCTION OF RADIUS OF WIRE

1 R cm.	2 V +Volts	3 E +Volts per cm.	4 E +Volts Calcul.	5 V —Volts	6 E —Volts per cm.	7 E —Volts Calcul.
0.00135	2720	2.74×10^5	2.62×10^5	2520	2.52×10^5	2.55×10^5
0.002185	3380	2.58	2.29	3230	2.45	2.23
0.0023	3500	2.25	2.09	3300	2.08	2.04
0.00258	3630	2.12	1.99	3500	2.02	1.94
0.00386	4060	1.66	1.67	4060	1.66	1.65
0.00678	5140	1.31	1.34	5320	1.36	1.33
0.00825	5710	1.25	1.25	6140	1.21	1.21
0.012	6600	1.07	1.09	6840	1.09	1.09
0.013	7180	1.07	1.06	7660	1.14	1.06
0.0205	8900	0.93	0.91	9370	0.99	0.92
0.0325	10880	0.80	0.79	11440	0.83	0.80
0.0385	11850	0.77	0.75	12400	0.79	0.76
0.0512	13500	0.71	0.69	14120	0.73	0.71
0.0642	14700	0.65	0.65	15220	0.64	0.64

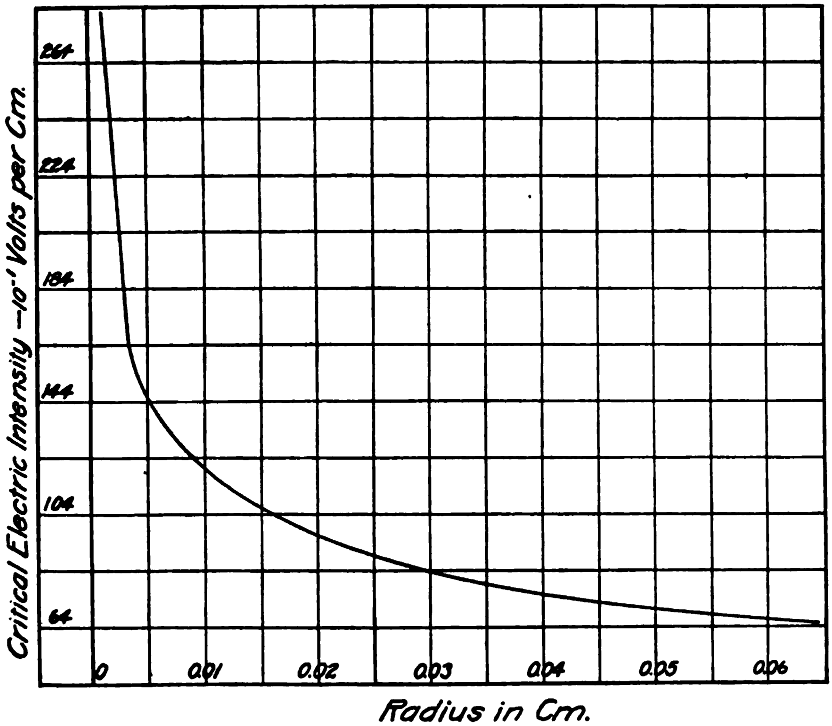

FIG. 10. CRITICAL ELECTRIC INTENSITY AT THE SURFACE OF THE WIRE AS A FUNCTION OF THE WIRE RADIUS

Peek has found that the following law, connecting electric intensity and radius, holds:

$$\epsilon = A + \frac{B}{\sqrt{a}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (2)$$

where A and B are constants and a is the radius of the wire. The data in columns 3 and 6 of Table 1 were obtained by substitution in equation (1) and columns 4 and 7 by substitution in the empirical law represented by equation (2). By comparing columns 3 and 4, and 6 and 7, one sees that for the smallest wires there are deviations from this formula. These deviations occur probably because the critical voltage and the glow voltage differ from each other, and because there is possibly a distortion of the field due to ionization before the glow begins. For the data given it is found that for the positive wire $A = 31.6 \times 10^3$, $B = 8.47 \times 10^3$; and for the negative wire $A = 35.0 \times 10^3$, $B = 8.06 \times 10^3$.

In hydrogen the relation between electric intensity and the wire radius follows equation (2) only approximately, and then only for wires whose radii fall within the limits from 0.1 mm. to 1.0 mm., and for gas pressures ranging from 100 mm. of mercury to atmospheric pressure. For wires of diameters larger than 1.0 mm., the ratio of the radius of the wire to the radius of the tube becomes comparatively small and the discharge phenomena change their character until with a No. 8 wire, 3.23 mm. in diameter, corona does not form at any pressure.

From the curves showing the relation between the critical voltage and the pressure, found by computing the electric intensity, curves could be drawn showing the relation between electric intensity and pressure.

Such curves taken from data with hydrogen can be represented nearly accurately by another one of Peek's formulas.

$$\epsilon = \epsilon_0\, p + c\sqrt{p} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (3)$$

where ϵ = critical electric intensity at wire,
p = pressure in percentage of atmospheric pressure,
ϵ_0 and c = constants.

These two laws of Peek can be combined into the one equation:

$$\epsilon = \epsilon_0\, p\left(1 + \frac{D}{\sqrt{ap}}\right) \quad . \quad . \quad . \quad . \quad . \quad . \qquad (4)$$

where ϵ_0 and D are constants, and a and p have the significance given to them. For both air and hydrogen it has been found that this law represents the facts only very approximately, especially is this statement true for large wires and low gas pressures. In hydrogen the critical and glow voltages have identical values for all sizes of wire and pressures studied.

12. *Theoretical Considerations.*—Several attempts have been made to give theoretical explanations of the corona discharge. No theory, however, has succeeded in explaining all the phenomena. In many cases the theory of spark discharge has been applied to the corona. Spark and corona are, however, different phenomena. In

the spark there is no distinction between positive and negative; whereas this distinction in the corona is very necessary. In order to start a spark a high potential difference, as a rule, is required; but as soon as the spark strikes, the potential difference falls to a very small value. This is not the case for the corona in air; moreover when the corona is started one has to raise the potential difference a great deal before a spark or rather an arc appears completely across the gas between the electrodes. In the case of the spark the striking potential difference, V, depends only on the pressure, p, of the gas and the distance, d, between the electrodes:

$$V = C p d$$

where C is a proportionality factor. This law is found by the following consideration. Suppose that there are a few electrons present in the gas in the natural state. If an electric force, $\epsilon = \frac{V}{d}$, is applied, and if λ is the average distance between successive collisions of an electron with a molecule, then this distance, λ, must be such that the force, ϵ, has time enough to impart to the electron the energy, E_c, required to ionize the molecule; hence

$$\epsilon = \frac{E_c}{\lambda} = \frac{V}{d}, \text{ or } V = \frac{E_c}{\lambda} d;$$

but λ, the distance between ionizing collisions, is inversely proportional to the pressure of the gas; hence $V = C.\,d.\,p$, or the striking potential difference, V, is constant if $p.\,d$ is constant. The spark depends only on the properties of the gas, especially on the mass of the gas between the two electrodes, but it is independent of the electrodes.

The apparent law of the corona discharge is quite different. The electric force, ϵ, which must be applied in order to start the corona discharge depends not only on the pressure of the gas but also on the radius of the wire approximately according to the expression

$$\epsilon = \epsilon_0\, p\left(1 + \frac{D}{\sqrt{R_p}}\right)$$

or for constant pressure: $\epsilon = A + \frac{B}{\sqrt{R}}$

For small wires a relatively strong electric force is required. A later chapter will show that not only the radius of the central wire but also its mechanical and chemical properties affect the initial discharge. At all events in the negative corona it seems as if the electrons were supplied in part by the metal and not only by the gas.

A partial explanation of the last formula can be given as follows: assume that in the neighborhood of the wire in a layer of constant thickness, δ, a certain constant energy is required for the beginning corona, different for positive and negative electricity; in fact the splitting up of the molecules into ions and the emission of light require energy. When a sufficient amount of energy is supplied, the breaking down of the dielectric accompanied by the luminous corona will occur. The thickness, δ, of the luminous layer seems nearly independent of the radius of the wire. In the neighborhood of the wire, the electric force, ϵ, assumes large values so that the polarization is also large and an opposing electric force, ϵ_0, of polarization will be created, so that the resultant electric force is equal to $\epsilon - \epsilon_0$. If k is the dielectric constant, R_1, the radius of the wire, then the energy, E_1, per unit length in a layer of thickness, δ, around the wire is:

$$E_1 = \frac{k}{8\pi} 2\pi R_1 \delta \, (\epsilon - \epsilon_0)^2$$

$$\epsilon = \epsilon_0 + \sqrt{\frac{4 E_1}{k R_1 \delta}}$$

If E_1, k, and δ are constant, then

$$\epsilon = \epsilon_0 + \sqrt{\frac{4 E_1}{k \delta}} \, \frac{1}{\sqrt{R_1}},$$ the law which approximately represents these observations.

The principle of similarity is now applied to two tubes, T and T'_1, where the linear dimensions are in the constant ratio of $1: z$, so that

$$R'_1 = R_1 z; \quad R'_2 = R_2 z; \quad \text{then } \epsilon_1 = \frac{V}{R_1 \log \frac{R_2}{R_1}}$$

$$\epsilon'_1 = \frac{V}{R'_1 \log \frac{R'_2}{R'_1}} = \frac{V}{R_1 z \log \frac{R_2}{R_1}} = \frac{\epsilon_1}{z},$$ provided the potential dif-

ference, V, is the same in both tubes. The discharge will start under the same potential difference if $p' = \frac{p}{z}$; then for the mean free paths in both tubes the relation is: $\lambda' = \lambda z$ and for the time intervals, t' and t respectively, between two successive collisions: $t' = t\,z$.
At any two corresponding points such as A and A' the electric forces are:

$$\epsilon = \frac{e}{r^2}, \qquad \epsilon' = \frac{ez}{r^2 z^2} = \frac{\epsilon}{z},$$

because it is assumed that at any moment the distribution and movement of the ions in the tubes are exactly similar, but that the total numbers are in the ratio of 1: z; hence

$$\epsilon'\,\lambda' = \frac{\epsilon}{z}\,\lambda\,z = \epsilon\,\lambda$$

$\epsilon\,\lambda$ is, however, the work done by the electric field during the motion of an ion over a mean free path; if after this mean free

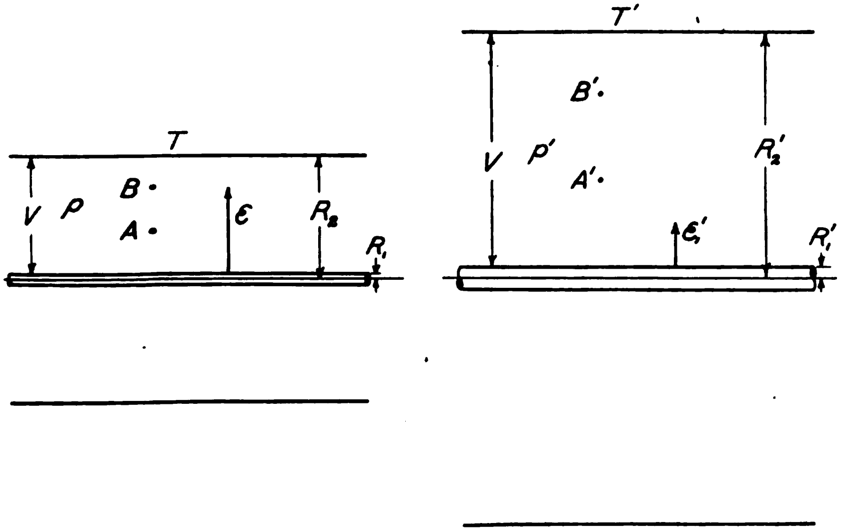

FIG. 11. THEORETICAL TUBES WITH LINEAR DIMENSIONS IN CONSTANT RATIO

path the next collision results in ionization, it will do so in corresponding points of both tubes. Moreover

$$\epsilon'_1 R'_1 = \frac{\epsilon_1}{z} R_1 z = \epsilon_1 R_1 \text{ and}$$

$$p' R'_1 = \frac{p}{z} R_1 z = p R_1; \text{ hence}$$

if $\epsilon_1 R_1$ is kept constant, then $p R_1$ remains constant; or $\epsilon_1 R_1$ is only a function of pR_1. If $\epsilon_1 = \epsilon_0 + \frac{b}{\sqrt{R_1}}$, then

$$\epsilon_1 R_1 = \epsilon_0 R_1 .1. + \frac{b R_1 1}{\sqrt{R_1 .1.}}, \text{ for } p = 1.$$

But if $R_1.1.$ is kept constant and is equal to $R_1 p$, then $\epsilon_1 R_1$ remains constant; hence

$$\epsilon_1 R_1 = \epsilon_0 R_1 p + \frac{b R_1 p}{\sqrt{R_1 p}}, \text{ or}$$

$$\epsilon_1 = \epsilon_0 p + \frac{b p}{\sqrt{R_1 p}}, \text{ or}$$

$$\epsilon_1 = p\left(\epsilon_0 + \frac{b}{\sqrt{R_1 p}}\right),$$

a rule approximately verified at least by experimental measurements in air.

CHAPTER IV

CHARACTERISTIC CURVES

A characteristic curve for the corona discharge shows graphically the relation between the voltage across the tube and the resultant current. Such curves will be considered in the following paragraphs for air and hydrogen at various pressures.

13. *Ampere-Voltage Characteristic Curves for Air at Atmospheric Pressure.*—It was found that the currents flowing, when the voltages were below the critical voltage, were negligible; consequently the following tests were started at a voltage somewhere near the critical voltage. For each voltage the deflection of the galvanometer was read for both polarities of the wire.

The presence of dirt or dust particles on the wire, when negative, has a marked effect upon the discharge. Often a spot or two on the wire would glow long before the wire as a whole was luminous. Because of this fact there is no definite critical voltage as in the positive polarity, for the initial jump of the deflection is much a matter of chance. As the voltage is increased, however, there occurs a critical voltage at which a flickering glow can be seen along the wire preliminary to the spreading of the discharge from a few spots over the whole wire. This phenomenon occurs at a definite voltage for a given size wire and it is this voltage which is given in the tables under ''visible glow'' for the negative polarity.

Fig. 12 shows the characteristic curves and critical voltage for copper wires of diameters ranging from 0.41 mm. to 1.28 mm.

A study of these data shows the following facts:

(1) For the smaller wires, the critical voltage is considerably lower than the glow voltage, and a fairly large current exists before a luminous discharge occurs. This statement applies to wire positive.

(2) The smallest wire, for which there is no current for wire positive before glow appears, is 0.135 mm. diameter.

(3) For wires larger than 0.135 mm. diameter, current and glow appear simultaneously, for wire positive.

(4) For wires about No. 26 and larger the current and the visible glow appear simultaneously, as a general rule, for the negative polarity.

14. *Characteristic Curves in Air at Reduced Pressures.*—It was discovered that a change in the pressure of the air in the corona apparatus had a marked effect upon the current caused by a given voltage; thus it was determined to obtain characteristic curves at reduced pressures for different wires. From such data it was hoped that the current readings for the different sizes of wire might be reduced to a 760 mm. basis. A series of characteristic curves was, therefore, taken for different pressures with dry air in the tube. Fig. 13 shows these results for No. 26 copper wire. These curves show a marked increase in the current for a relatively small decrease in

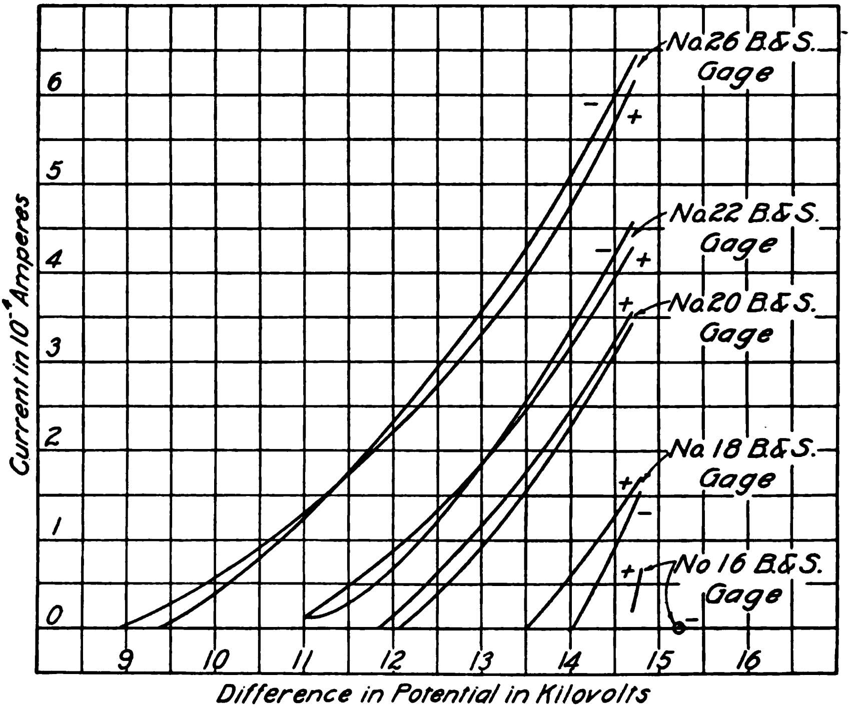

FIG. 12. CHARACTERISTIC CURVES FOR THE CORONA DISCHARGE WITH VARIOUS WIRE DIAMETERS

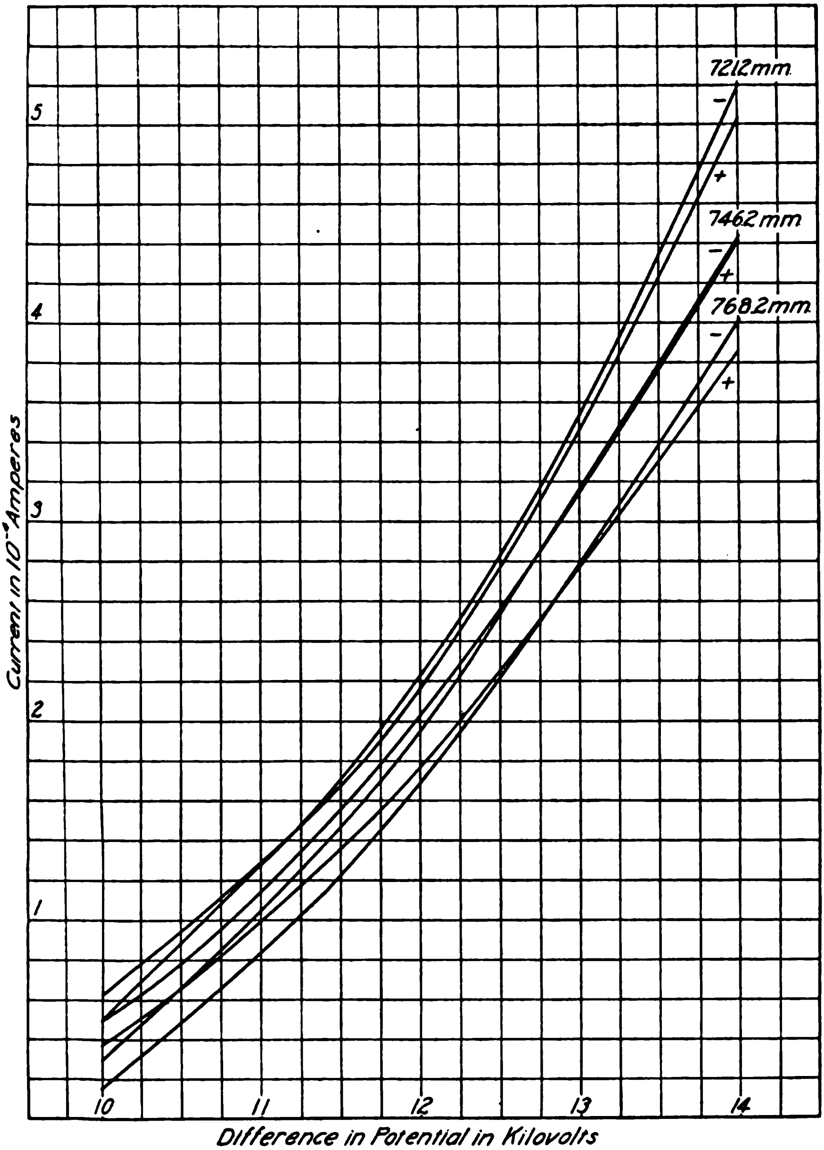

FIG. 13. CHARACTERISTIC CURVES FOR NO. 26 B. AND S. GAGE COPPER WIRE WITH AIR UNDER VARIOUS PRESSURES

the pressure. The curves also show an unsymmetrical spacing which suggests the presence of some disturbing factor.

In a number of preliminary experiments it was found to be impossible to repeat observations if the tube was closed and the air not changed. In order to eliminate any disturbing effects due to moisture in the air and possible changes in the constitution of the air in the tube, an arrangement was devised for supplying dry air which could be pumped through the tube out into the atmosphere. The air was dried by being passed through wash bottles containing sulphuric acid and then through a tube containing soda-lime. Fig. 14 shows the results when No. 40 wire was used. These curves show a regular effect of pressure which is larger for the negative than for the positive corona. This regularity seems to indicate that the discordant results

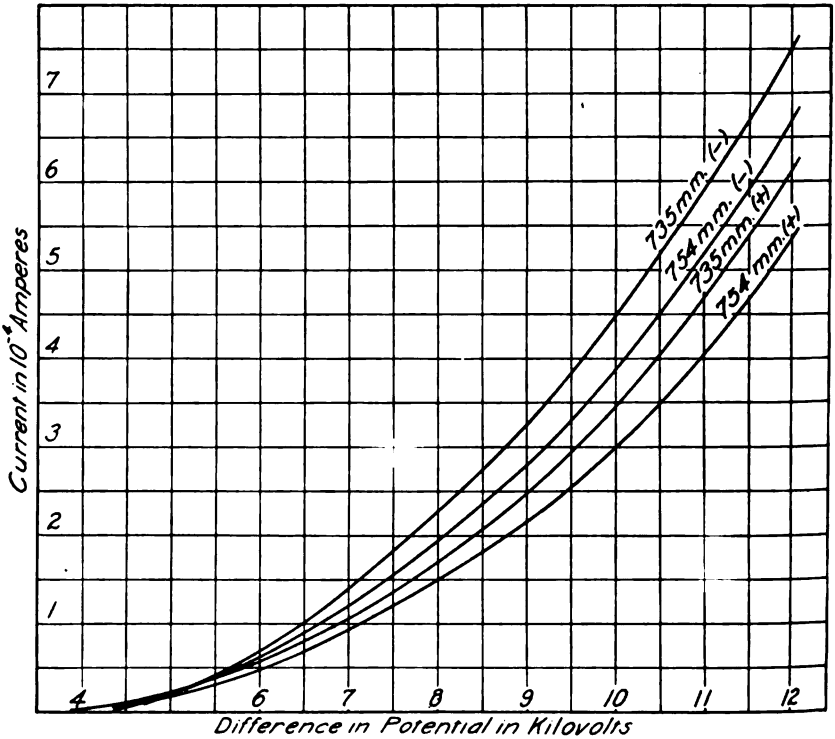

FIG. 14. CHARACTERISTIC CURVES FOR NO. 40 B. AND S. GAGE COPPER WIRE WITH DRY AIR UNDER VARIOUS PRESSURES

obtained in the preliminary experiments were due to the presence of other factors rather than mere change of the pressure.

To determine the effect, if any, of confining air in a closed tube upon the coronal current a series of tests was run under constant pressure with various conditions as, for examples, the closing of the tube, the renewal of the air. The erratic results which followed showed no evident relations and indicated that confinement of the air has a great effect upon the coronal current and also upon the critical and visible glow voltages. Such an effect does not appear strange when one thinks of the ozone, and possibly other products formed which, when the tube is closed, must remain inside and thus change the character of the gas to a considerable extent. It must be concluded from these tests that it is unsafe to compare results obtained in a closed tube with those obtained where there is a plentiful supply of fresh air.

15. *Characteristic Curves in Hydrogen at Atmospheric and Reduced Pressures.*—Some characteristic curves for positive corona in hydrogen are given in Figs. 15 and 16. The most remarkable points about these characteristics are:

(1) The marked difference between the critical voltage and the voltage at which corona ceases.

(2) The difference between the points taken with increasing and those taken with decreasing current.

This persistence of corona at voltages less than that necessary to start the discharge has not been observed with air and continuous potentials.* If there is any such difference for air, its magnitude is certainly very much less than with hydrogen.

This difference between the critical voltage and the voltage at which corona is maintained may be explained by the change in the electric intensity (volts per centimeter) at the surface of the wire after the corona has formed. This change of intensity is caused by the space charge due to the positive and negative ions in the space between the wire and the tube. That such a distortion of the electric field exists will be shown later. The difference between the critical

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*See Bennett, A. I. E. E., Proc. Vol. 32, Part II, p. 1796, 1913, for alternating potentials.

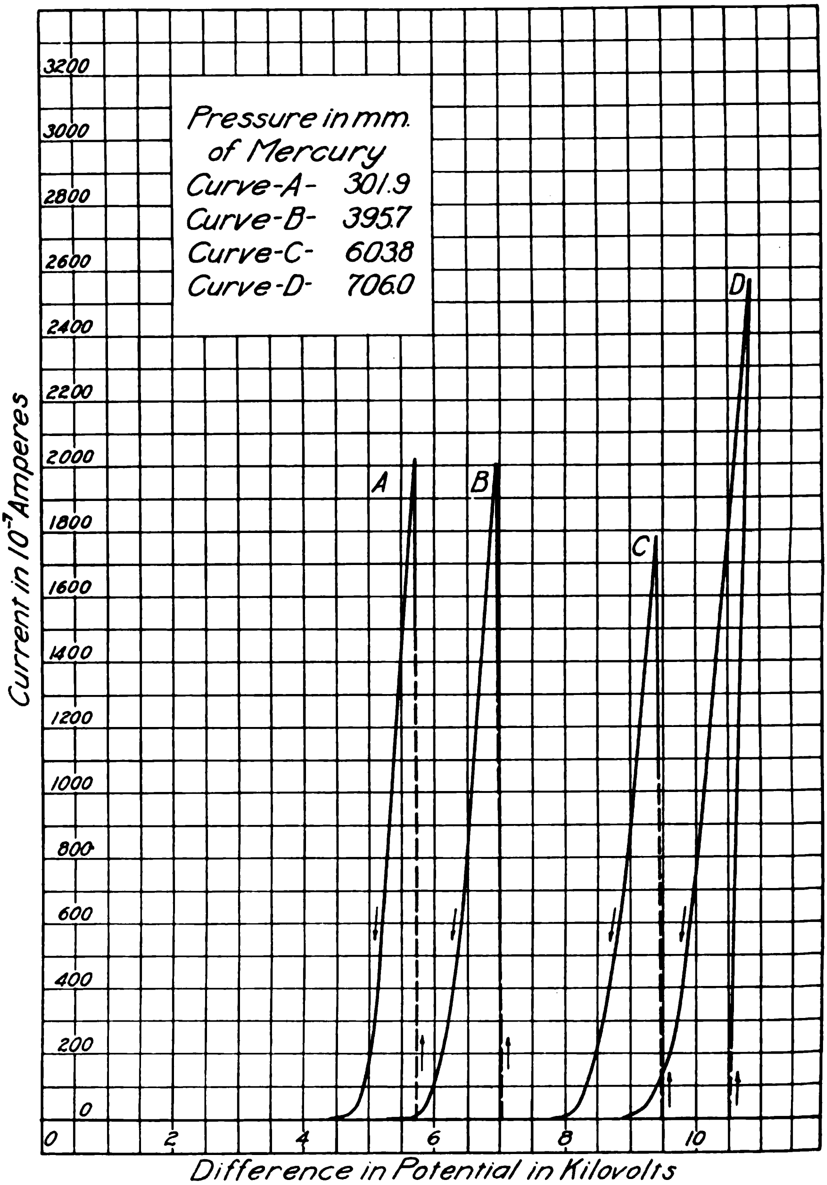


FIG. 15. CHARACTERISTIC CURVES FOR NO. 14 B. AND S. GAGE COPPER WIRE IN HYDROGEN FOR VARIOUS PRESSURES, WIRE +

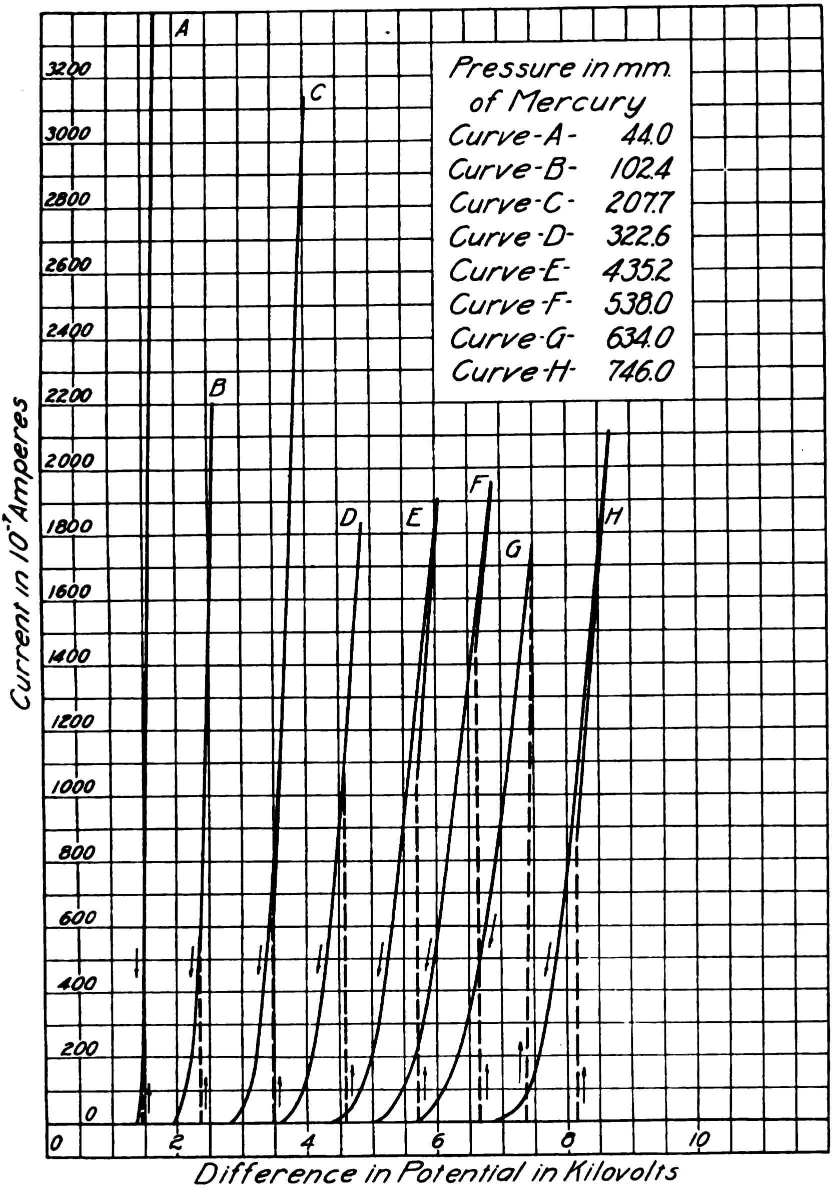


FIG. 16. CHARACTERISTIC CURVES FOR No. 20 B. AND S. GAGE COPPER WIRE IN HYDROGEN FOR VARIOUS PRESSURES, WIRE +

voltage and the voltage at which the discharge ceases is not detected unless all sources of irregular ionization, such as rough spots on the wire, high intensity where the wire passes through the glass, etc., are eliminated.

Other properties of the characteristic curves are:

(3) For a given voltage the current increases with a decrease of density of hydrogen.

(4) For a given voltage the current increases with a decrease in wire diameter.

(5) The characteristic curve is very nearly parallel with the current axis so that a small change in potential produces a very great change in current.

(6) As soon as the copious ionization stage is reached, the current rises to a high value. For wires as large as No. 8 the current increases immediately to arcing values. As the size of the wire is decreased the initial jump diminishes until with a No. 32 wire (0.200 mm. in diameter) at atmospheric pressure the current rises to a value of the order of 10^{-4} amperes.

(7) With a single size of wire and varying pressures, the initial current rise diminishes with a decrease in pressure.

Characteristic curves for negative corona for various pressures and two sizes of wire are given in Figs. 17 and 18. The full line curves represent stable conditions and a constant number of beads. The number of beads on any particular curve may be determined by noting the small number adjacent to the curve. In the small wire it will be noticed that the shape of these characteristics depends to a large extent upon the gas pressure.

With the smaller wire (No. 36 diameter .0121 mm.) the corona seemed to start in each case with a number of very small bright points on the wire. Usually, however, the negative corona started with an unstable flickering glow along the wire. With an increase of voltage the current gradually increased until a point was reached where the small bright spots combined into one negative bead of the kind described in Chapter II. This change in formation was accompanied by a large increase in current and by a drop in the potential difference between the wire and the tube. This drop in potential difference across the tube was, in a certain sense, due to the resistance

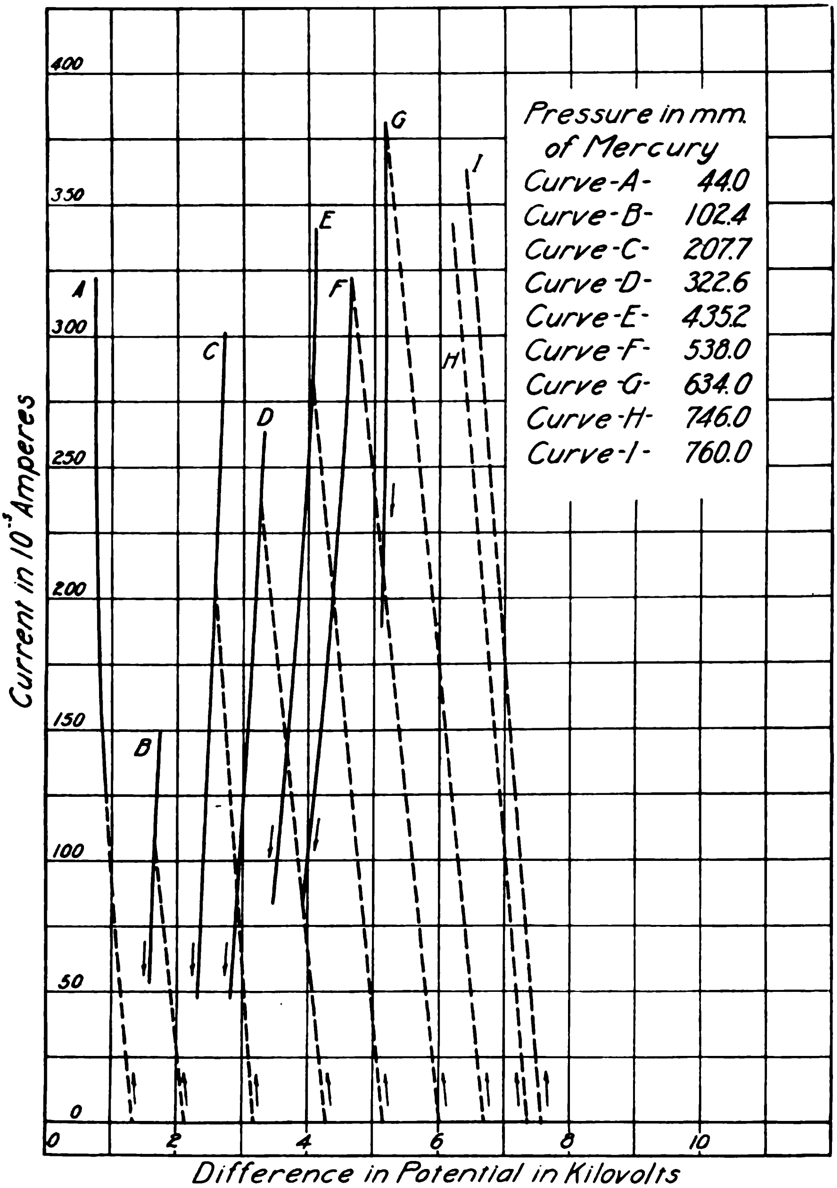


FIG. 17. CHARACTERISTIC CURVES FOR NO. 20 B. AND S. GAGE COPPER WIRE IN HYDROGEN FOR VARIOUS PRESSURES, WIRE –

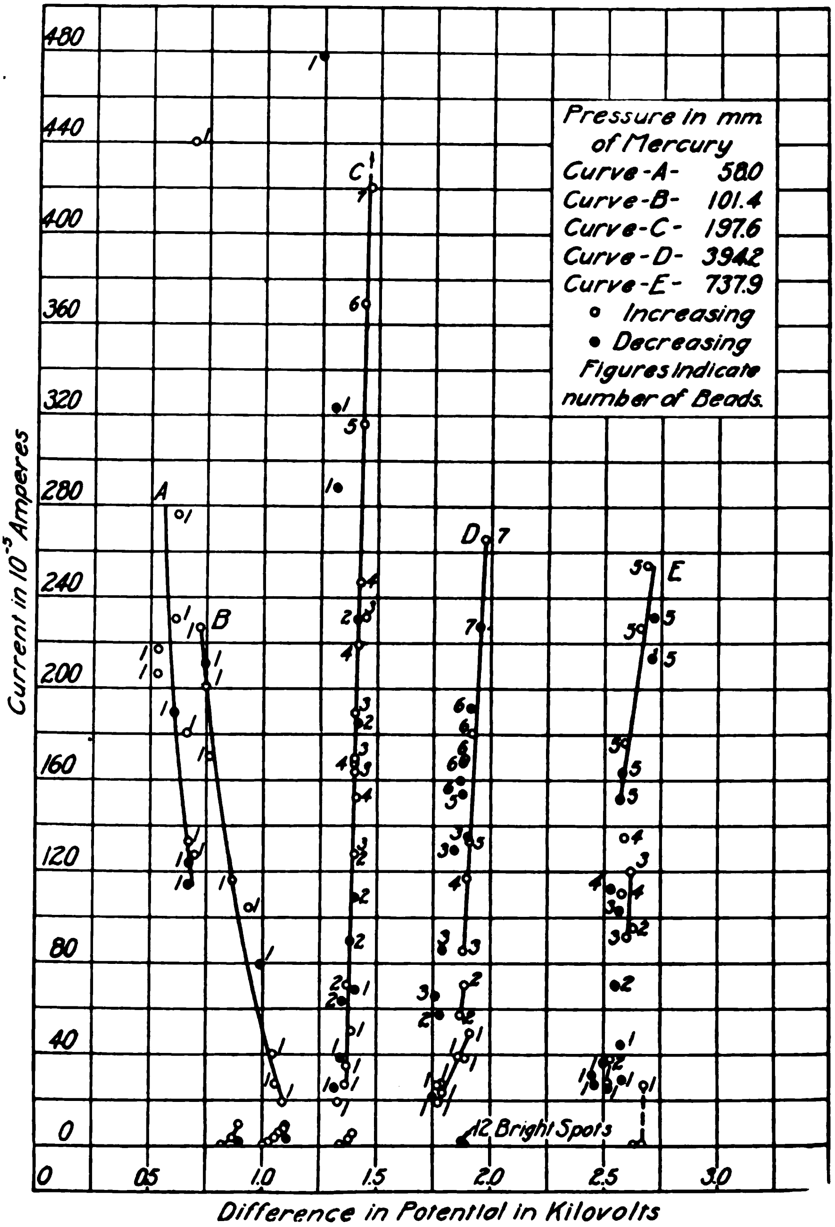


FIG. 18. CHARACTERISTIC CURVES FOR NO. 36 B. AND S. GAGE COPPER WIRE IN HYDROGEN FOR VARIOUS PRESSURES, WIRE —

in series with the corona tube. The increased current taken by the tube causes a higher drop through the series resistance. This increased drop stabilizes the corona discharge and prevents the indefinite increase of current which might result if there were no resistance in the circuit. The gaps in the curves represent unstable conditions. An increase in the generated voltage caused an increase in the corona current, which was accompanied by either an increase or a decrease of the voltage between the wire and the tube depending on the size of wire and the gas pressure.

It may be noticed that for the lower pressures the characteristics are similar to the usual arc characteristic. The discharge, however, was not that of the arc. The arc formed if the machine voltage was sufficiently increased. This increase was accompanied by a further drop in the voltage between the wire and tube and an entire change in the general appearance of the discharge.

The study of the negative characteristics leads to the following conclusions:

(1) For larger wires the curves for a constant number of beads have positive slopes at all pressures above 100 mm.

(2) For a given wire and gas pressure the curves become more nearly parallel with the current axis as the current increases in value.

(3) For a given number of beads and a constant pressure the maximum possible voltage variation is approximately a constant, whatever the number of beads.

(4) With a constant radius and a decreasing pressure the curves revolve in a counter-clockwise direction about their lower points until their slopes change from positive to negative values. The discharges become unstable at the point of infinite slope and resemble the arc discharge in so far as this property is concerned.

(5) With a constant pressure and decreasing radius the critical electrical intensity decreases, and the slopes of the curves approach negative values.

(6) In all cases, as the voltage is gradually increased through the critical value, the beads form one by one, the current values at any time being approximately proportional to the num-

ber of beads. The initial current values never became excessive as they do with the positive corona discharges.

(7) For a given voltage the current increases with a decrease of gas density and also for a decrease of wire radius.

(8) The greater the number of beads on the wire the greater the current change per unit change of potential.

(9) For all but the smallest wire studied the first corona discharge takes the form of beads. For the smallest wire the first discharge at pressures below 200 mm. of mercury takes the form of a flickering unstable glow traveling along the wire. This glow condenses to small, flickering, and unstable beads upon a slight potential increase. These flickering beads persist until currents of the order of 10^{-4} amperes are obtained; then they condense to the ordinary bead discharge.

CHAPTER V

ADDITIONAL FACTORS AFFECTING THE STARTING POINT AND THE CORONA CURRENT

The characteristic and starting point curves show the effect upon the corona current of varying the radius of the wire and the pressure of the gas. In addition to these the following variables also affect the current.

16. *Moisture.*—The effect of moisture has been studied only when air was the dielectric. An arrangement was devised whereby air could be drawn from the room through the tube. The humidity of such air was given by calculation from the readings of wet and dry bulb thermometers. Parallel sets of readings of the current flowing when dry air was pumped continuously through the tube and when air from the room was sucked through before each reading were taken from day to day. The results are shown in Fig. 19. These curves indicate a regular effect due to moisture, with a tendency for the decrease of current by humidity to be greater for negative polarity of the wire. The decrease of current by the presence of moisture is well known; so these results agree with present knowledge.

To determine whether the presence of moisture in the air has an effect upon the critical voltage, a test was run as follows under a pressure of 736 mm. and humidity 68.5 per cent. Air was drawn from the room through the tube, and the voltage was noted at which the initial jump of the galvanometer occurred for wire positive. The positive glow voltage and the negative glow voltage were then determined. Then dry air was pumped through the tube and the same measurements were taken. The results were:

	Wet Air	Dry Air
Positive critical voltage	4300	4190
Positive glow voltage	4350	4260
Negative glow voltage	4275	4370

The effect of moisture apparently is to raise slightly the starting point of the positive corona, but the reverse is true for the negative polarity.

The appearance of the discharge is also affected by moisture, when the wire is negative. With moist air in the tube, the discharge begins with dim spots, and the discharge is of no clearly defined nature, being a mixture of sections of continuous glow and bright spots which are immobile.

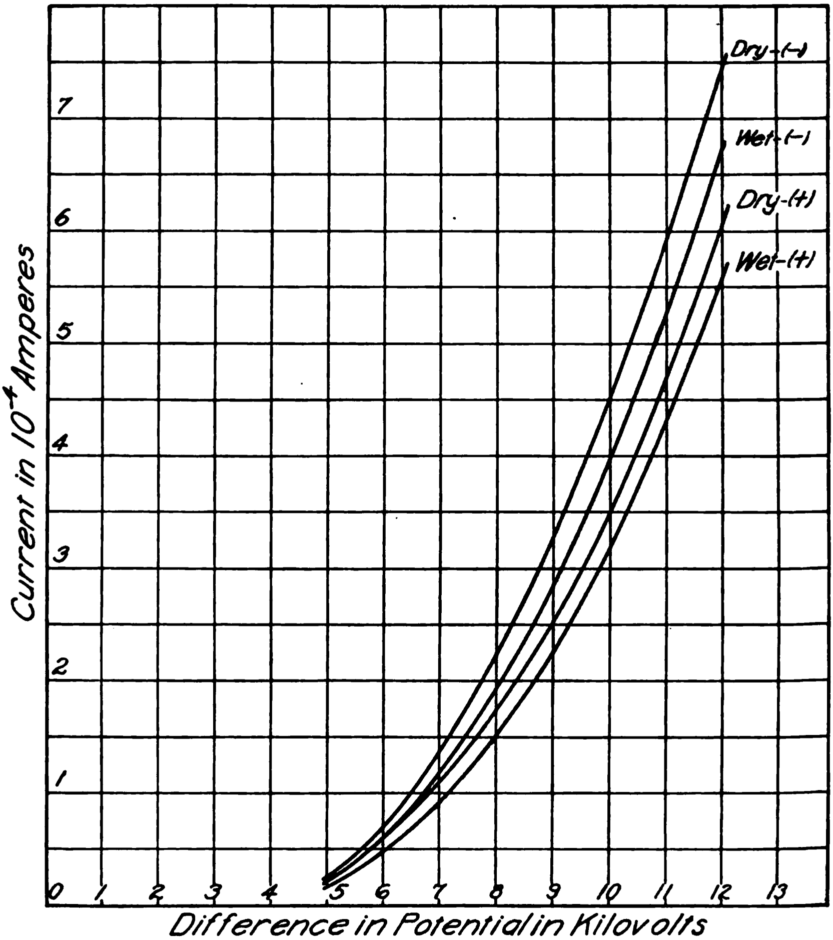


FIG. 19. EFFECT OF HUMIDITY UPON THE CORONA CURRENT

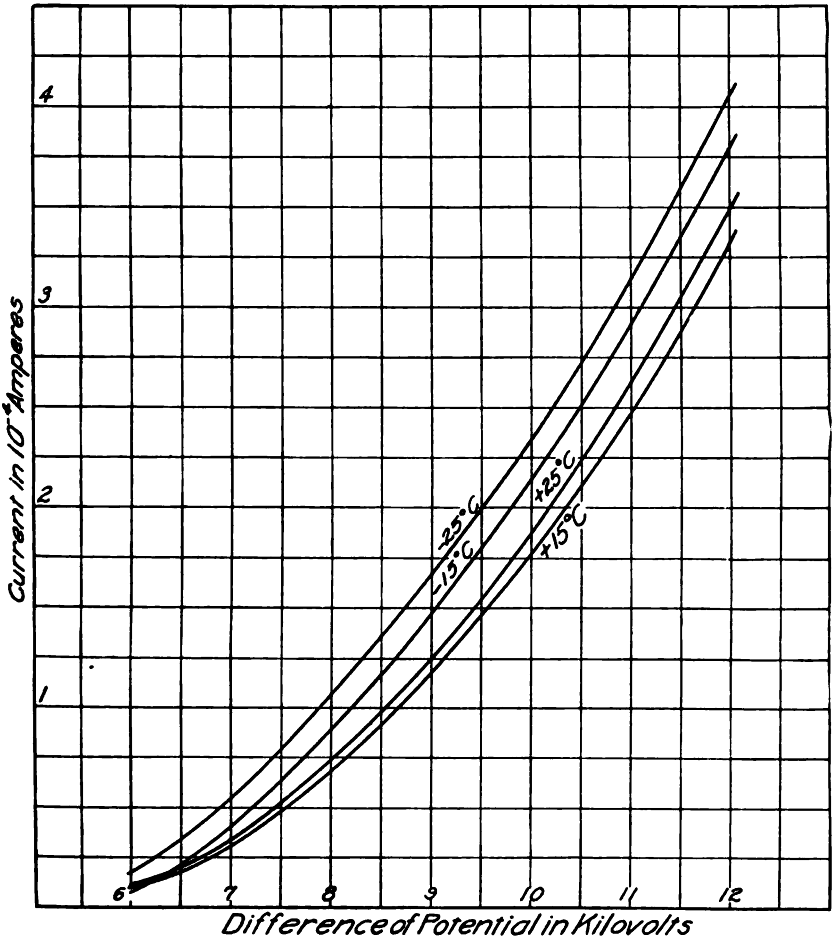


FIG. 20. INFLUENCE OF TEMPERATURE UPON THE CORONA CURRENT AT A CONSTANT PRESSURE OF 760 MILLIMETERS

The effect of moisture on the appearance of the negative discharge was shown by the following experiment: The tube was filled with moist air, and a voltage somewhat above the critical value was impressed. A mixed discharge resulted as was described in the preceding paragraph; then a current of dry air was started through the tube, and little by little the discharge cleared up and resolved itself into a line of uniformly spaced brushes which were in continual agitation. When moist air was again admitted, the discharge resumed its former character.

With moist air in the tube and a fairly high potential difference the wire vibrates circularly for both polarities, and describes a torpedo-like figure of revolution. The filling of the tube with dry air diminishes considerably the amplitude of the vibration for wire positive and stops the vibration entirely for wire negative.

17. *Temperature.*—The influence of temperature upon the current for a No. 36 copper wire in a closed tube under a pressure of 760 mm. was determined for the temperatures 15 degrees C. and 25 degrees C. The results appear in Fig. 20. The lower temperature was obtained by placing cloths wet with alcohol upon the tube and directing a stream of air from a fan upon it. The curves indicate that this difference of temperature makes a far greater difference in the current for wire negative than for wire positive, both currents showing an increase for higher temperature as might be expected.

18. *The Nature of the Surface of the Wire and the Metal of the Wire.*—The fact that the starting point of the negative corona was influenced by dust particles on the wire suggested that a careful study should be made of the corona from different surfaces and from different wires: It was decided to use wires having polished, corroded, and mechanically abrased surfaces. The results will be shown in the following paragraphs:

(1) In the preparation of the polished surfaces care was taken in choosing wires without kinks or surface scratches. These wires were polished with fine emery cloth and finished with chamois and jeweler's rouge just before they were placed in the tube.

The abrased surfaces were prepared by rolling the wire in emery powder between two hard plane surfaces. Care was taken to have the surfaces abrased uniformly over the whole length.

The corroded surfaces were prepared by different methods. The surface of the steel wire was corroded by a solution of nitric acid, which made a black surface. The aluminum wire was corroded by allowing it to remain in a solution of sulphuric acid for a few days. The result was a thin white coating. For copper it was necessary to oxidize the surface by passing a heating current through the wire in the presence of oxygen. Since ozone is produced by the corona discharge in air, the silver wire was coated with a layer of silver peroxide by allowing the corona to play on the wire for some time.

(2) The results of starting voltages for different surfaces and wires are shown in Table 2.

TABLE 2

COMPARISON OF STARTING VOLTAGES FOR DIFFERENT SURFACES AND WIRES
All wires about 0.41 mm. diameter

Polished			Abraded			Corroded		
Press. mm.	Wire Volts. −	+	Press. mm.	Wire Volts. −	+	Press. mm.	Wire Volts. −	+
COPPER								
50	1 700	1 780	53.2	1 680	1 820	50.3	1 650	1 660
252	2 650	2 600	253	2 550	2 800	250	2 010	2 500
731	6 010	5 760	743	5 600	6 200			
STEEL								
51.6	1 710	1 710	52.2	1 690	1 740	52.3	1 750	1 700
252.4	2 600	2 600	253.2	2 770	2 770	252	2 550	2 710
727.6	5 660	5 960	736	4 560	5 830	739.4	4 810	5 760
ALUMINUM								
50	1 760	1 720	52	1 660	1 800	51.9	1 240	1 690
251	2 820	2 900	251.5	2 490	2 900	252	2 370	2 660
741.1	5 880	6 180	741	5 010	5 800	745.3	4 680	5 880
SILVER								
53.2	1 850	1 820	52.3	1 730	1 740	52.5	1 850	1 780
252.1	3 150	3 050	252.2	2 600	2 900	252.2	3 150	3 000
744.8	4 210	6 130	743.2	5 060	5 850	746	5 760	6 320

The results shown in this table can be discussed for each of the surface conditions of the wire, and for each condition three pressures will be considered.

(3) The general appearance of the corona is the same for all polished positive wires and differs only slightly for negative wires at different pressures. At pressures of nearly 50 mm. when the potential is brought up to the glow potential, wire positive, a very faint flashing glow appears over the whole length of the wire and becomes uniform and steady as the potential is raised slightly. The potential may be carried up to the arcing point without changing the gen-

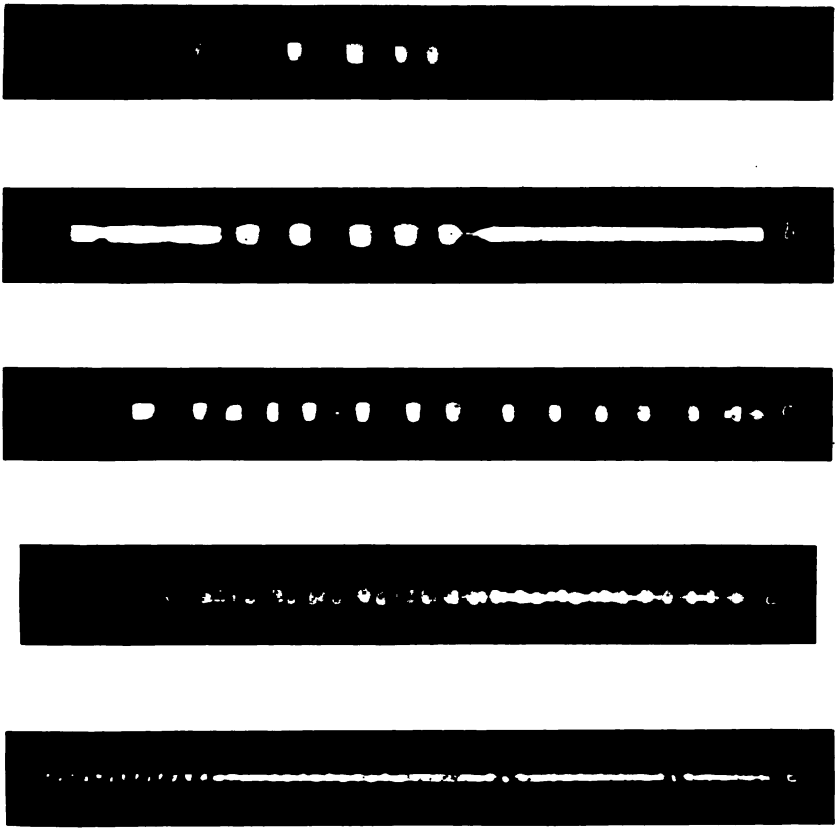
eral appearance of the uniform glow. The only noticeable change is an increase in the brightness of the bluish glow.

For pressures of 50 mm. and for negative wire, the first appearance of the corona is a flashing glow, similar to that for positive wire but of much greater diameter and brightness. Increasing the potential causes this glow to remain steady on the wire, to become uniform and to be very bright. Very little current flows until a stage is reached not far above the starting point, where the bright uniform glow breaks into large, clear, characteristic, negative beads. The current then increases rapidly with the potential. As the potential is increased the beads increase in number but remain large and well defined.

For the polished surfaces and with a pressure of 50 mm. the negative corona on copper begins at a lower potential than the positive. Corona appears at the same potential for both polarities in steel, but for aluminum and silver the positive glow begins at the lower potential. Table 2 shows no general law. With the exception of the silver wire at a pressure of 746 mm. the starting potential for the corroded wire is smaller for both polarities than for the polished wire. For the negative abrased wire the starting point is in general lower than for the polished wire with only two exceptions. With the exception of silver the starting point of the abrased positive wire is higher than that of the polished wire. With increasing pressure the differences involved by abrasion and corrosion diminish. The largest influence is found for aluminum wire, negative corroded at 51 mm.

For pressures of nearly 250 mm. the glow for wires positive is the same as for pressures of 50 mm., being uniform and increasing in brightness as the potential increases. For wires negative and polished it is almost impossible to break the glow up into clear-cut beads at this pressure. With increasing potential the glow becomes brighter and condenses at certain ill-defined points, apparently attempting to form beads, but these condensed regions move rapidly back and forth along the wire.

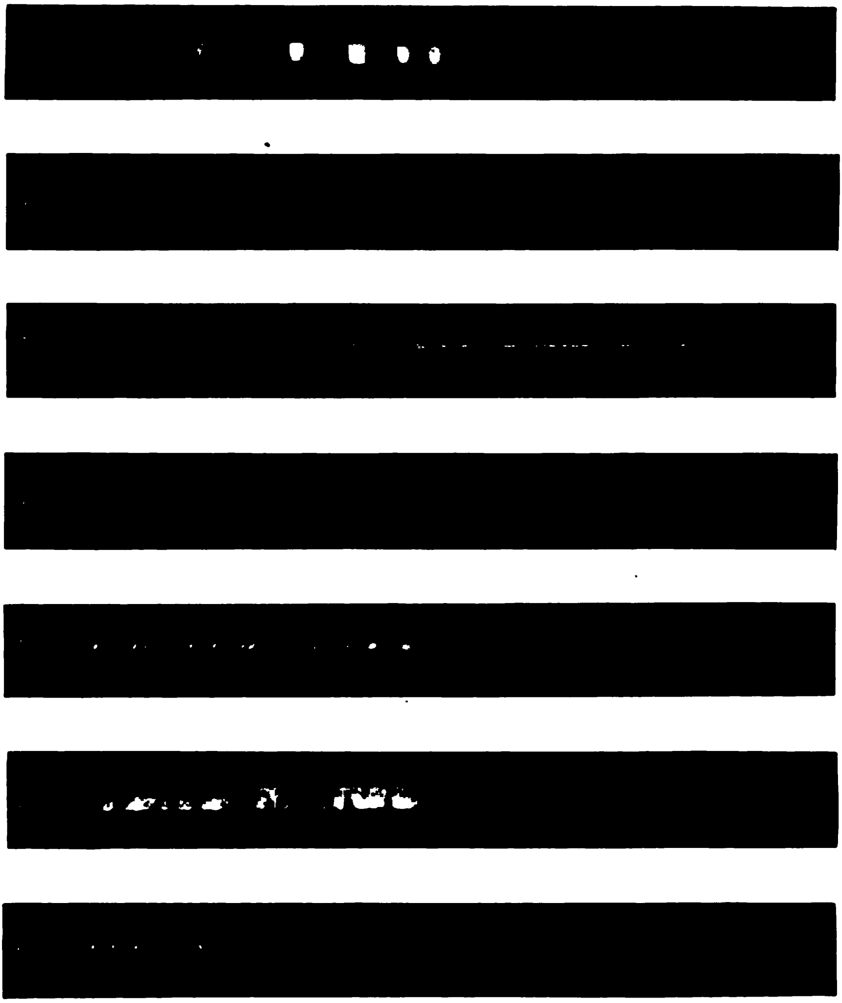
For atmospheric pressure, wires polished and positive, the glow appears faint but uniform and increases in brightness as the potential is increased. For negative wires a faint flashing glow appears at break-down potentials and increases in brightness with the potential increase. A very few scattered beads form at times, but they are small and unstable with very rapid lateral motion. This motion



Steel Wire, 0.28 mm., Diameter
All Wires Negative

	Voltage	Pressure
a	990	21 mm.
b	1080	25 mm.
c	1400	39 mm.
d	2300	68 mm.
e	8900	370 mm.

Fig. 21. A Comparison of the Glow on Abrased, Polished, and Corroded Surfaces of Steel Wire



Enameled **Polished**

German Silver Wire, 0.65 mm., Diameter

		Voltage	Pressure
a	Wire +	1460	23.5 mm.
b	Wire +	1700	25.5 mm.
c	Wire +	1830	35.5 mm.
d	Wire +	2800	91.5 mm.
e	Wire −	3920	185.5 mm.
f	Wire +	4400	185.5 mm.
g	Wire +, Arc in Series	4450	185.5 mm.

Fig. 22. A Comparison of the Glow on Enameled and Polished Surfaces of German Silver Wire

increases in amplitude and speed with increasing voltage. Clear cut beads over the whole wire are impossible here as in the last case.

(4) With wire surface mechanically abrased or roughened and pressure of 50 mm., the positive glow begins with faint flashes as with the polished surfaces; then becomes steady and uniform and increases in brightness as the potential is increased. The starting glow voltage is in general higher than for the positive polished wires, and is also higher than for the abrased negative wires. For wires abrased and negative the corona begins with bright flashes of a fuzzy glow, part of which may have one or two large flashing beads. This flashing glow seems to pulsate in synchronism with the impulses of the driving machinery. A slight potential increase above the first noticeable glow causes the glow to break into well-defined beads which soon become steady and clear and which increase in number with a potential increase. The negative starting voltage for abrased wires is lower than for the polished surfaces.

For wires abrased and pressure of 250 mm. the positive visual glow is the same as for pressure of 50 mm. The positive starting potential is in general higher than for the negative abrased and also positive polished surfaces. The negative glow voltage causes very faint "spears" or small brushes of light to flash from sharp points here and there on the rough surface. These spears increase in size and number with increased potential, some being much brighter than others. As the potential is increased these spears unite into definite, clear beads which at times may be very steady and at other times may have more or less violent lateral movements. The negative starting voltage for abrased surfaces is much smaller than for the polished surfaces.

At atmospheric pressures the positive glow on the abrased wire surfaces usually begins with a few small flashing purple streamers or brushes extending from the wire almost to the tube. These streamers are similar in appearance to the positive fans and to the streamers emitted from the surface of the enamel covered wire, Figs. 21 and 22. These streamers increase in brightness and are accompanied by a soft glow as the potential is increased. After a certain increase in the voltage has taken place, these streamers disappear and only the uniform glow remains and increases in brightness.

For the abrased negative wire at atmospheric pressure the corona starts with small flashing spears the same as for the abrased wire at

250 mm. These spears increase in number very rapidly with an increase in voltage, some of them collecting, so to speak, into small bright beads and then breaking up again. As the potential continues to increase, the beads become more steady and definite, so that at times the abrased wire may be covered with many small, bright, steady, and evenly spaced beads.

(5) The positive visual corona for corroded surfaces is essentially the same for all pressures as has been described for the abrased surfaces. At low pressures it begins with a faint flashing glow which becomes steady and uniform and which increases in brightness. At pressures of 250 mm. the appearance is the same as described for the abrased surfaces, and for atmospheric pressure the corona may start with the small purple brushes or fans and an accompanying flow, the fans soon disappearing and the glow becoming uniform and increasing in brightness. The positive glow generally begins at lower voltages for the corroded surfaces than for the polished surfaces.

The negative visual corona for the corroded surfaces is likewise similar to that for abrased surfaces at different pressures. Clear cut and steady beads are obtained at the lower pressures but are not so stable for the higher pressures. In general the negative starting voltage is lower than for polished surfaces.

(6) In order to show a few results photographically a wire having one-third of its length polished, one-third corroded, and one-third mechanically abrased was placed in a tube with a longitudinal slot, and photographs were taken when the corona was on the wire. Fig. 21 contains photographs of the negative wire, the left end being abrased, the center polished, and the right end chemically corroded.

These photographs show that the beads begin on the polished surface, that the corroded surface shows no glow, and that the abrased surface has only a slight brush discharge on it. The beads on the polished surface are very large, clear, steady, and evenly spaced. Fig. 21, *b* shows the effect of a slight increase in voltage where the glow now appears on the corroded surface and the beads begin to form on the abrased surface. Gradually increasing the voltage and the pressure as well causes the glow to become brighter on the polished surface and the beads to increase in number on the abrased and corroded surfaces. The beads on the abrased portion have a lateral movement, while those on the polished part are still very steady and clear.

With a still greater increase in pressure and voltage it is possible to reach a condition where the whole length of the wire is covered with clear, steady, and evenly spaced beads (Fig. 21, *c*). Here it seems that the surfaces all act very nearly the same in the formation and building of the corona discharge.

When the pressure is increased to 370 mm. and the voltage is sufficiently high to produce the discharge, the corona starts first on the abrased portion and only on this part can steady, clear beads be obtained (See Fig. 21, *e*). The beads on the corroded part are fairly well defined, but they are in an agitated state. Under these conditions it is found impossible to get steady beads on the polished part of the wire; instead of the clear beads there is a rather knobby glow on the wire, the condensations in which seem to be beads trying to form.

This reversal of the phenomena, the clear beads forming on the polished surface at low pressures and on the abrased surface at high pressures as shown in Fig. 21, actually occurred for steel wire. The corona starts first on the polished wire for low pressure and begins on the abrased or corroded wire at much lower potentials for high pressures.

An enameled german silver wire was fitted into the tube after half of its length had been freed from the enamel and polished. At low pressures for the positive wire the characteristic glow appeared on the polished end. The enameled end had several small starlike spots of light which were irregularly distributed and which appeared at points where the insulation had failed. Keeping the wire positive and increasing the voltage caused very bright "streamers" of purple light to shoot from a few of these small stars. At higher pressure and higher voltage these streamers increased greatly in number, the glow spreading out into a thin fan-shape. This fan slowly oscillated about the bright spot on the wire as a center. Between the fans a hazy fog-like glow was present. When an arc was placed in series with the wire and the tube, this fog disappeared and the fans became more sharply defined and steadier than they were.

For the wire negative (see Fig. 22, *e*) it was not possible under any conditions to get the characteristic negative beads nor could a glow be produced on the polished end. The only discharge present was on the enameled end and was similar in appearance to the small stars for the positive wire. For the negative wire, however, the stars were intensely bright and in slight movement. Fig.

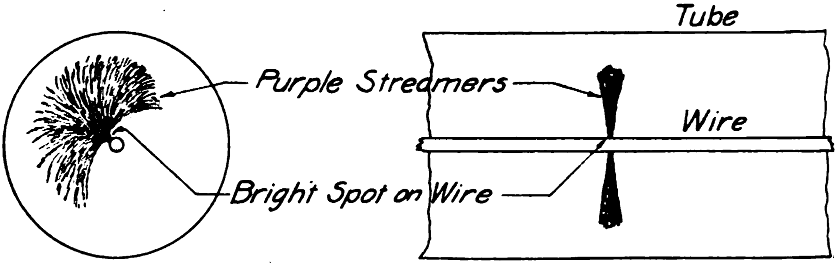


FIG. 23. STRUCTURE OF THE POSITIVE PURPLE FANS, UNDER CONDITIONS GIVEN IN FIG. 22.

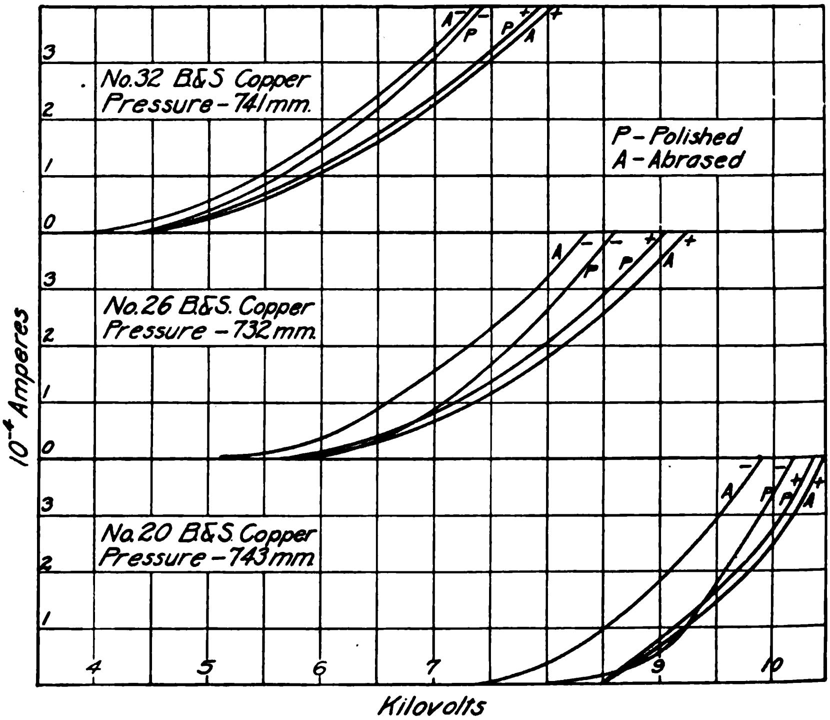


FIG. 24. CHARACTERISTIC CURVES FOR COPPER WIRES WITH VARIOUS RADII AND SURFACES

22 shows the appearance of the discharge from the enameled wire when it is both positive and negative. Fig. 23 gives details of the structure of the positive purple fans. For the enameled wire negative the starting potential was much lower than for the opposite polarity.

(7) The curves in Fig. 24 are taken for varying sizes and different surfaces of copper wire.

In *e*, Fig. 22, the surprising fact is shown that the negative discharge passes through the enameled part of the wire, while the free metal surface shows no trace of a glow. The curves show that the effect of abrasion in general lowers the starting point for copper wires at atmospheric pressure. The curves for the negative abrased wire are widely displaced from those of the polished wire; thus it is shown more current flows in the corona discharge for the same voltage for wire abrased than for the smooth wire. The curves showing the discharge for the positive abrased wire quickly cross those for the polished wire and then continue to rise slightly displaced, less current flowing for the same potential abrased than for polished. The abrased surface has, thus, the effect of restraining the flow of the positive current.

The effect of abrasion is much greater in the negative than in the positive current. The curves also show that this effect is greater for the larger wires, as might be expected. The higher starting potential for the larger wires is also evident.

The negative current builds up very slowly at first on the polished surface but finally reaches a point where it builds up much faster than the positive, and at this point the beads are formed. The starting voltage for the abrased surface negative is much lower than for polished surface negative. The characteristic curve of the abrased wire is a smooth rising one which eventually crosses the polished negative curve for large current values. This same phenomenon has been observed for different metals.

Fig. 25 gives the characteristic positive and negative curves for aluminum wires at about 50 mm., and shows the effect of the three surface conditions,—namely, polished, abrased, and corroded. The starting positive wire voltage for the smooth surface is slightly lower than that of the negative, but the curves cross low, the positive current building up slowly with increased potential while the negative curve is almost a straight line which rises very rapidly. The positive starting potential is higher for the abrased surface than for the polished, while that for the negative abrased surface is lower. The negative polished and abrased surface curves cross, but the positive do not. For the corroded surface the positive glow voltage is about the same as for the polished surface, the curve for the former condition becoming displaced shortly, less current flowing for the same voltage. The negative starting potential is very much lower in the latter case than that for the polished surface, but crosses at a low current value and rises to the right, less current flowing for the same potential.

Thus it is seen that the surface condition has a very marked

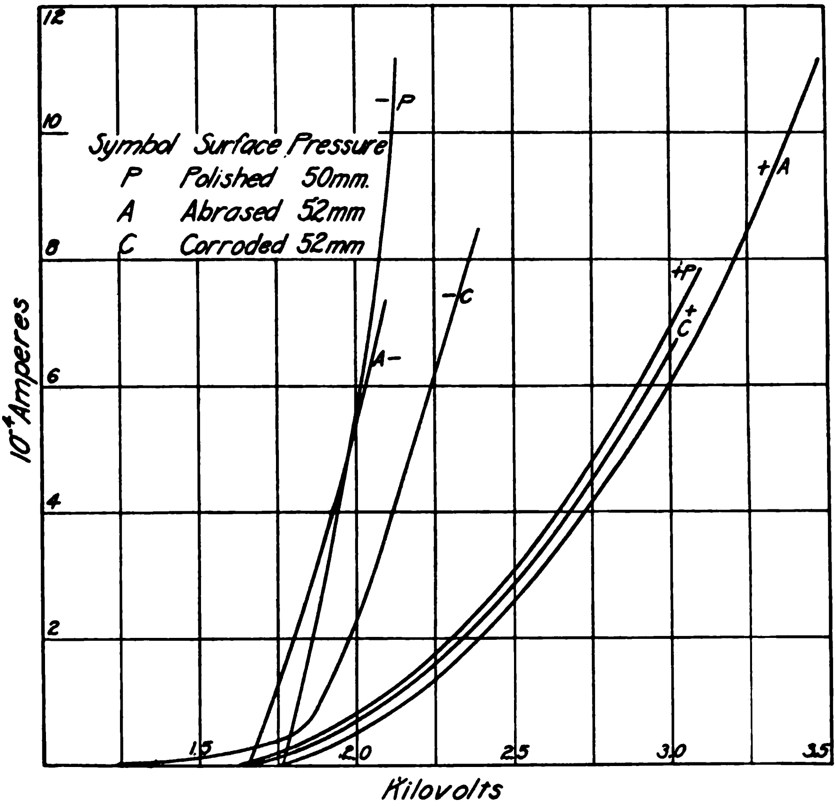


FIG. 25. CHARACTERISTIC CURVES FOR ALUMINUM WIRE OF 0.45 MM. DIAMETER WITH VARIOUS SURFACES

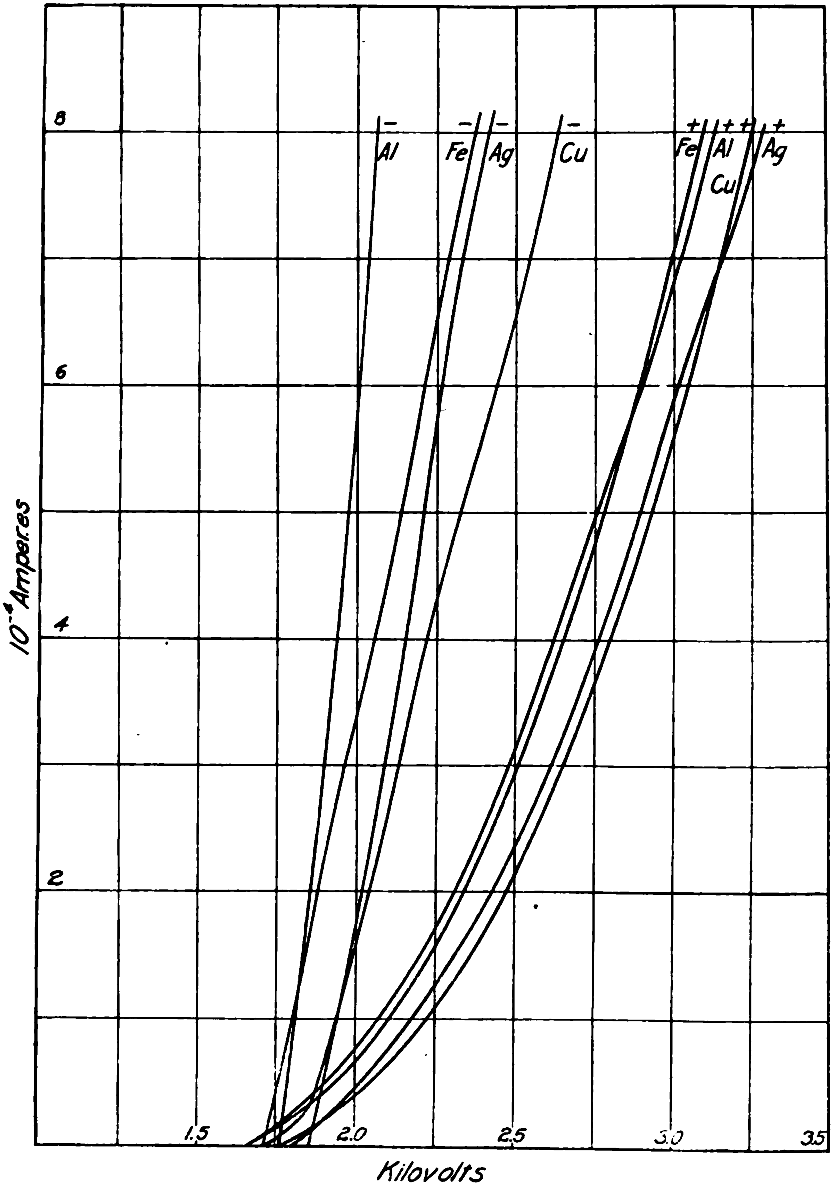


Fig. 26. A Comparison of the Characteristic Curves Series of Different Metals

effect on the starting point of the corona as well as on the characteristic curves. All the wires were about 0.41 mm. in diameter. In general the abrased surface has the effect of lowering the starting potential for negative wire and raising it for positive wire. The starting point for both positive and negative corona in the case of corroded wires is in general lower than that for the polished surfaces, but the corroded surface characteristics behave in rather an erratic manner, sometimes being displaced in one way and sometimes in the opposite.

Table 3 gives a comparison between the corroded and polished wire characteristics for both positive and negative surfaces at different pressures.

The curves in Fig. 26 show a comparison between the characteristics of different metals. Very marked differences are evident in the characteristic curves and show directly that the metal itself has a

TABLE 3

COMPARISON OF CORRODED WITH POLISHED WIRE CHARACTERISTICS

Wire	Press	Starting Pot.	Corroded Surface Characteristic
		COPPER	
−	50.2	Lower	Raised
+	50.4	"	"
−	250.0	"	Crosses high
+	250.8	"	Raised
		STEEL	
−	53.2	Higher (press. diff.)	Crosses high
+	52.4	Lower	" "
−	252.0	"	" low
+	252.4	"	Lowered
−	739.4	"	Crosses high
+	739.4	"	" low
		ALUMINUM	
−	51.9	Lower	Crosses low
+	51.9	"	" "
−	252.0	"	" midway
+	252.0	"	Raised
−	745.3	"	Crosses midway
+	745.4	"	Raised
		SILVER	
−	52.5	Same	Lowered
+	52.5	Lower	"
−	252.2	Same	Crosses low
+	252.2	Lower	" midway
−	745.8	Higher	Lowered
+	746.1	"	"

part to play in the corona formation. The positive and negative characteristics, especially for aluminum, become widely separated for large currents. The curves for the other metals separate at different rates for increasing current values, but in such a manner that each metal behaves in its own characteristic way.

Slight differences in the starting points for the different metals were noticed; these differences, however, are of such a nature that they cannot be explained as being experimental errors. Steel and copper seem to have about the same starting point, while that for aluminum is a little higher and silver has a value still greater. The different metals not only affect the behavior of the characteristic curves but also the starting points of the corona glow.

The formation and number of the negative beads depend not only on the pressure and potential, but also on the surface condition and the material of the wire. The current per bead is larger for the abrased and corroded surfaces than for the polished surface, with the assumption that the whole current is to be carried by the beads. For an increase in pressure it is also seen that the current per bead is much less for the polished surface than for the others, but the beads are smaller in size. For the higher pressures it takes, however, a larger voltage to produce the same number of beads. For the lower pressures the beads have about the same degree of stability for all the different surfaces, while for higher pressures the beads are more stable on the abrased or corroded surfaces than on the polished, it being almost impossible to get definite beads on the polished wire for atmospheric pressures.

The number of beads increases rapidly with increasing voltage. Here again the effect of the materials is compared. For the production of the same number of beads it takes in general a greater voltage on the steel than on the copper and aluminum wires.

CHAPTER VI

ALTERNATING CURRENT RECTIFICATION

19. *Suggested by a Comparison of the Air and Hydrogen Characteristic Curves.*—Fig. 9 shows that the discharges through air and hydrogen were very similar in so far as the variation between critical voltage and radius and pressure are concerned. The curves in Fig. 27 show clearly the difference between the corona in air and in hydrogen. The two curves on the left side of the figure refer to

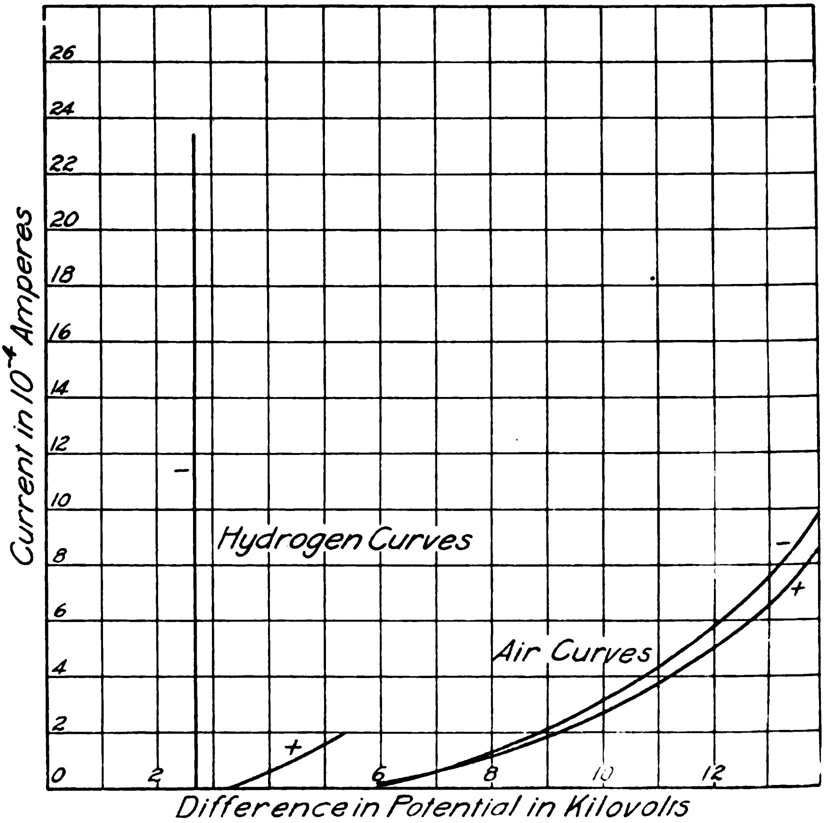


FIG. 27. COMPARISON OF CORONA IN AIR AND HYDROGEN UNDER SIMILAR CONDITIONS

hydrogen, while the curves on the right show results obtained with air. The data for these curves were obtained with wires of approximately the same diameter. These curves show two distinct differences between corona in air and in hydrogen.

In air the positive corona starts at a lower voltage than the negative, while the reverse is true when the dielectric is hydrogen. The other and more important difference is the entire dissimilarity of the positive and negative curves with hydrogen. This difference has not been found with air. A single glance at this curve shows that corona in hydrogen between a wire and a tube is an effective means of accomplishing rectification. This statement is true since large currents may be obtained from a negative wire with voltages which will give little or no current from a positive wire. This rectification may be accomplished with the wire cold and is not a case of rectification by means of a hot cathode. The principal of electron emission from a hot cathode might be used, however, in connection with the corona rectification.

20. *Description of Apparatus and Tests.*—To show that rectification was possible the corona tube was connected to an alternating source of voltage. A sensitive oscillograph element was connected directly in series with the corona tube and another element was connected across the primaries of the transformers. A diagram of the connections is shown in Fig. 28.

21. *Oscillograms and Their Interpretation.*—Fig 29 gives the current and voltage curves when an alternating voltage is impressed across a corona tube. The curve having both positive and negative lobes represents the voltage. The non-symmetrical character of this curve is due to the drop in the resistance in series with the primaries of the transformers. The curve lying mainly below the axis represents the current flowing between the wire and tube. The part of this curve slightly above and slightly below the axis is of the same shape and order of magnitude as the charging current of the condenser formed by the wire and cylinder. This fact was determined by an oscillogram taken at a voltage slightly less than that necessary to form corona.

The voltage at which negative corona starts, as shown in this oscillogram, is approximately twice the voltages across the tube at the instant that the discharge ceases.

The rectification with corona in hydrogen is practically perfect as is shown by the oscillograms in Figs. 29 and 30.

In an investigation, interrupted by the World War, J. W. Davis has shown that alternating currents may be perfectly rectified up to 42,000 volts made effective by means of the corona in hydrogen. The rectification is, however, not of very high efficiency as a large part of the energy is transformed into heat in the corona tube. For a given gas pressure the maximum voltage which may be rectified or, in other words, the voltage at which the arc sets in between the coaxial cylinders is nearly directly proportional to the radius of the outer cylinder, when the radius of the inner cylinder is small compared with that of the outer cylinder. In order to improve the efficiency of the rectification the central wire was heated. An incandescent wire gave rise to the corona discharge at voltages much lower than those necessary to start a discharge from a cold wire. The initial state of ionization around the wire has a very marked effect on the critical corona voltage. When the central wire is heated to incandescence and then the high voltage applied, the temperature of the wire will change very much, especially towards the ends where the wire appears almost dark, while in the middle the temperature may fall to that of dull red heat. This fall of temperature is undoubtedly due to the wind set up in the corona. Fig. 31, from Davis' unpublished paper, will show a rectification at 42,000 volts.

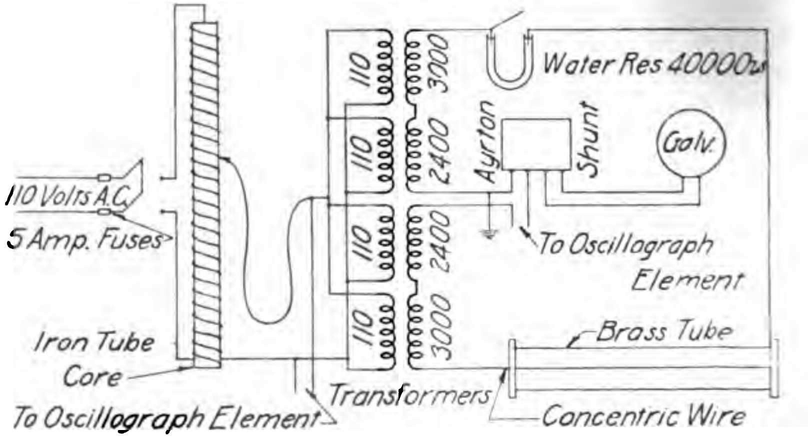


FIG. 28. DIAGRAM OF CONNECTIONS FOR ALTERNATING CURRENT RECTIFICATION IN HYDROGEN

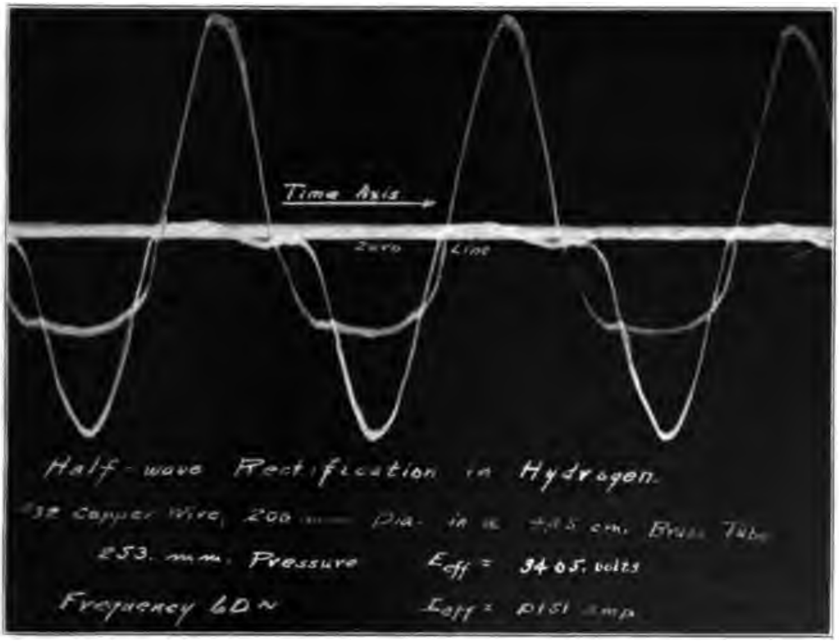


FIG. 29. OSCILLOGRAM

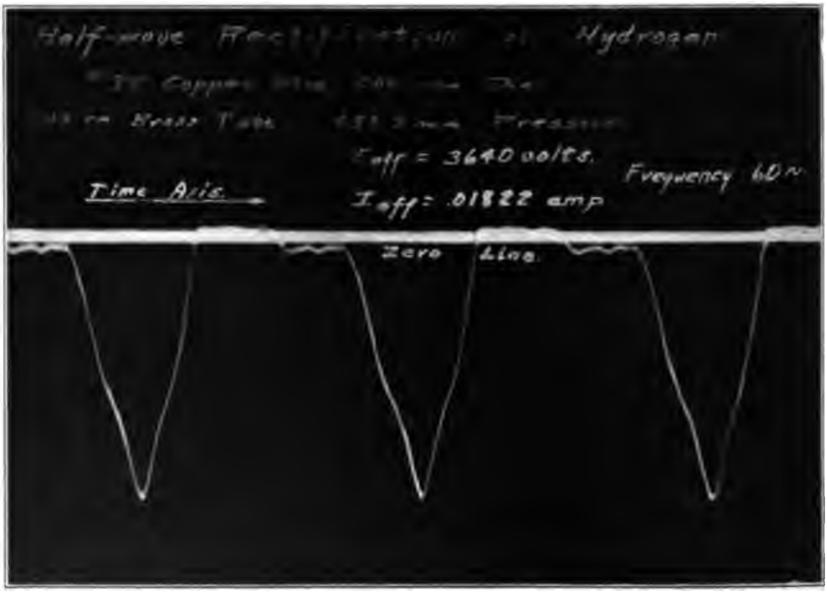


FIG. 30. OSCILLOGRAM

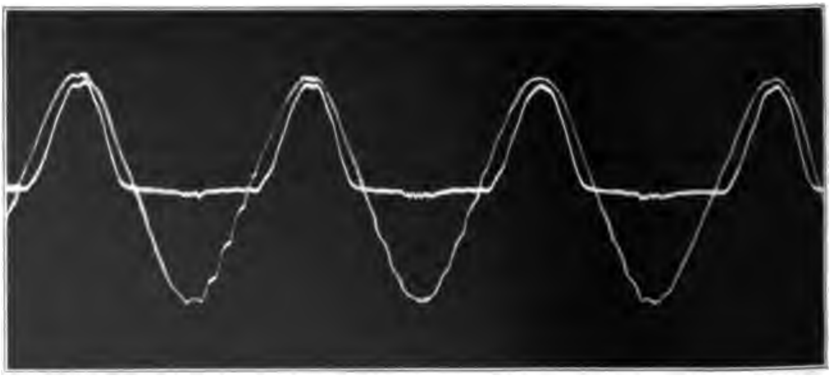


FIG. 31. OSCILLOGRAM SHOWING RECTIFICATION AT 42,000 VOLTS

CHAPTER VII

DISTRIBUTION OF POTENTIAL IN THE CORONA TUBE

In order to develop any complete corona theory a knowledge of the distribution of the potential between the electrodes is necessary. The distribution of potential between the wire and the coaxial cylinder was investigated in the following manner.

22. *Method and Apparatus.*—A hole was drilled in the side of a cylinder, and an insulated wire terminating in a bare spherical tip was arranged so that it could be moved radially between the wire and the tube. A micrometer microscope directed on a fixed point of the movable wire served to determine the relative position of the point. An electrostatic voltmeter of small capacity was connected in series with the exploring point and the tube.

When the point was moved to any position in the radial field, the voltmeter quickly showed a constant deflection and indicated that the potential of the point was in equilibrium with that of the field at that particular place. By moving the exploring point from the tube

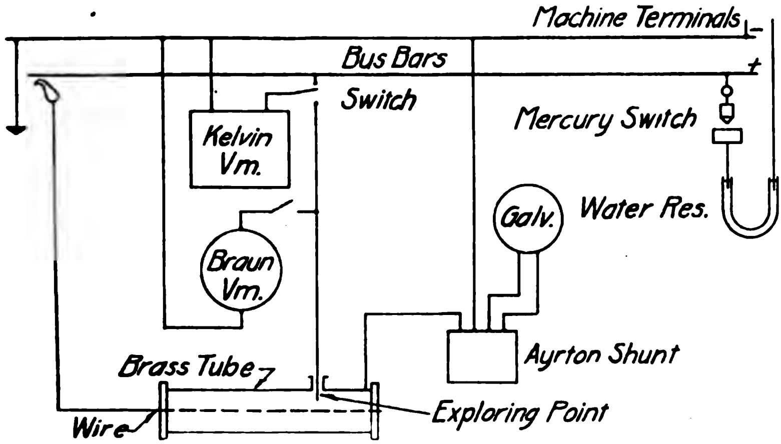


FIG. 32. DIAGRAM OF CONNECTIONS OF APPARATUS FOR DETERMINING THE DISTRIBUTION OF POTENTIAL IN THE CORONA TUBE

to the wire and observing the voltmeter readings at certain intervals, one obtained a comparatively accurate estimate of the intensity of the field. The apparatus and connections are shown in Fig. 32. The tube used in this investigation was 35.5 cm. long and 7 cm. in diameter. The wire was copper, well polished, and stretched tightly. In all, four wires were used, No. 40, No. 32, No. 28, No. 20, B. & S. gage. Since it was necessary to work at pressures lower than atmospheric,

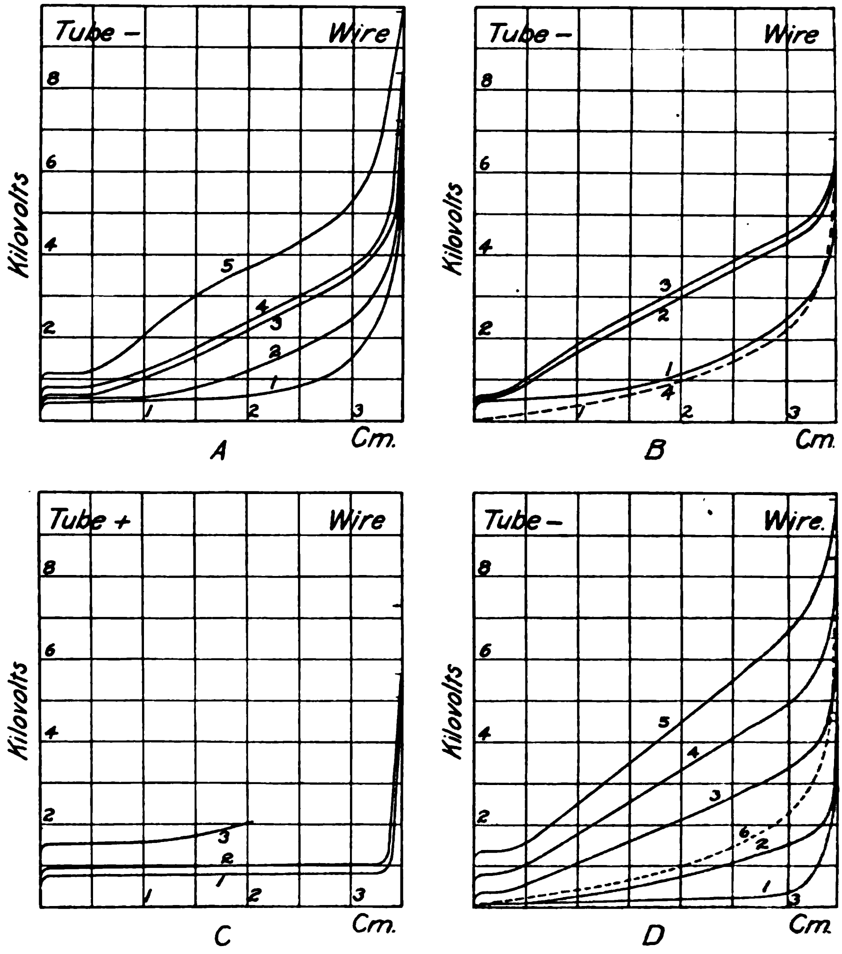


FIG. 33. REPRESENTATIVE CURVES SHOWING DISTRIBUTION OF POTENTIAL IN THE CORONA TUBE

a glass tube was sealed over the exploring rod and arranged with ground points and springs so that the point might move at will without destroying the constant pressure.

23. *Results Obtained.*—By this method, curves were taken for various pressures and voltages after the appearance of the corona. Representative curves are shown in Fig. 33, and the conditions under which each curve was taken are given in Table 4.

For the smaller wires it was found difficult to obtain data for curves when the wire was negative, because the voltmeter would not come to rest and give a definite reading. For a No. 32 wire, when the wire was negative, two curves shown in Fig. 33*C* were taken before the corona appeared, also a portion of a curve for a voltage at which there was a distinct series of beads along the wire.

Curves were also obtained for No. 28 and No. 20 wire when the wires were negative, the same general characteristics being exhibited in each.

Curve 4, Fig. 33*B*, shows the distribution of potential as given by electrostatic theory. This theory assumed, of course, that there are no charges in motion in the gas: that is, that there is no current. It is seen that the actual distribution is very different from what it

TABLE 4

TABLE OF DATA FOR CURVES

Figure	Curve	Wire B. & S. Gage	Voltage	*I* Amperes	*P* Mm. of Hg.	Temp. C.	Remarks
33*A*	1	32	6 510	$4.17.10^{-8}$	747	25°	No glow
	2	32	6 825	$1.91.10^{-6}$	747	26°	Distinct glow
	3	32	7 425	$1.91.10^{-5}$	747	26°	Good glow
	4	32	8 400	$5.94.10^{-5}$	747	26°	Good glow
	5	32	9 900	$9.54.10^{-5}$	747	26°	Bright glow
33*B*	1	32	6 825	$1.91.10^{-6}$	747	26°	Distinct glow
	2	32	6 825	$2.03.10^{-4}$	241	24°	Bright glow
	3	32	6 825	$3.46.10^{-4}$	885	24°	Brilliant glow
	4	32	6 825	Electrostatic	curve		
33*C*	1	32	5 050	$1.79.10^{-8}$	744	26°	No glow
	2	32	5 650	$2.39.10^{-6}$	744	26°	A few dull beads
	3	32	7 250	$3.10.10^{-5}$	744	26°	Beads 1 cm. apart
33*D*	1	40	4 520	$4.77.10^{-8}$	740	22°	No glow
	2	40	4 700	$1.19.10^{-6}$	740	22°	Distinct glow
	3	40	6 500	$2.26.10^{-5}$	740	22°	Good glow
	4	40	8 400	$8.29.10^{-5}$	740	22°	Good glow
	5	40	9 900	$1.67.10^{-4}$	740	22°	Brilliant glow
	6	40	8 400	Electrostatic	curve		

would be if there were no current. The detailed discussion of the curves will be considered under the two polarities.

In general for the positive wire the space between the anode and the cathode may be broken up into four regions:

> (1) A region immediately surrounding the wire, which is characterized by a very large potential gradient. This gradient may be due to the excess of the number of ions or electrons approaching the electrode over the number of those leaving, since the former number includes ions generated at all parts of the field; whereas the latter contains only ions that are generated in the narrow layer close to the wire. It is, therefore, evident that the charges on the excess of negative ions near the wire disturb the electric field so that the potential difference per centimeter, or the gradient, is large near the surface of the wire.
>
> (2) A region of approximately constant force extending from the "surface layer" region adjacent to the wire to a point which varies with the pressure, current, and voltage. At the higher voltages, the actual potential at a given point in this region is greater than the theoretical electrostatic potential, and the tangent to the curve may be either greater or less.
>
> (3) A region of little or no force near the tube, but not touching it.
>
> (4) A region adjacent to the tube, where positive charges accumulate and form an abrupt cathode drop of potential.

When the wire is negative and corona appears, a potential curve is obtained which differs somewhat from the positive curves. Large cathode and anode drops appear, and the intervening space has a very small field. Reasoning similar to that which explains the shape of the curves when the wire is positive explains the negative curves.

So in general, the anode and cathode drops of potential are predominant in both types of curves. There are several reasons for this: namely,

(1) Polarization potential between a metal and a gas.
(2) Accumulation of ions.
(3) Reflection of ions.
(4) Different velocities of positive and negative ions.
(5) A non-uniform field.

For a system where the potential at a point is due to moving charges as well as static charges, there is Poisson's equation expressing the density in terms of the potential

$$\Delta^2 V = -4\pi\rho,$$

or, expressed in cylindrical coördinates,

$$\frac{\delta^2 V}{\delta r^2} + \frac{1}{r}\frac{\delta V}{\delta r} + \frac{1}{r^2}\frac{\delta^2 V}{\delta \phi^2} + \frac{\delta^2 V}{\delta z^2} = -4\pi\rho$$

For this particular case, the derivatives in z and ϕ are zero; so rewriting this equation and using total derivatives gives

$$\frac{d^2 V}{dr^2} + \frac{1}{r}\frac{dV}{dr} = -4\pi\rho = \frac{1}{r}\frac{d}{dr}\left(r\frac{dV}{dr}\right). \quad . \quad . \quad . \quad (8)$$

Since the density is an undetermined function of the radius, the equation cannot be integrated directly. If, however, the potential is plotted against the distance from the axis, a graphical method will aid in the determination of the density; that is, if the first derivative

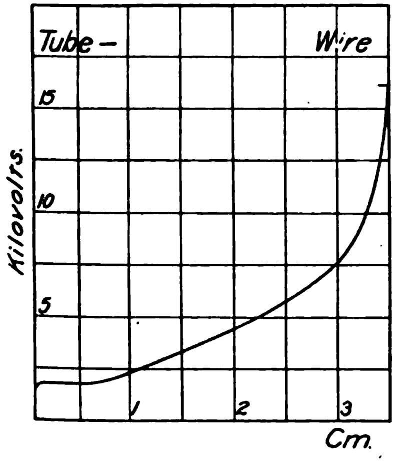


FIG. 34. EXPERIMENTAL CURVE OF DISTRIBUTION OF POTENTIAL IN THE CORONA TUBE

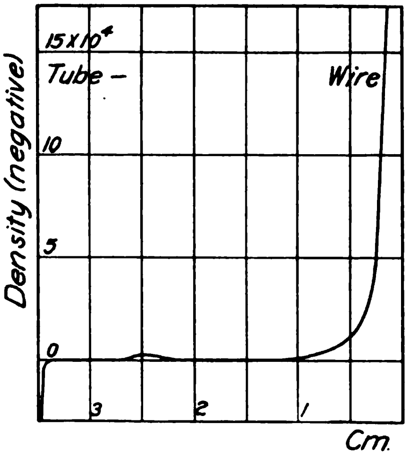


FIG. 35. COMPUTED CURVE OF THE VOLUME DENSITY OF ELECTRIFICATION IN THE SPACE BETWEEN THE WIRE AND THE TUBE

of the potential is determined from the curve for a series of values of *r*, these new values may be plotted against the radius again. Repeating this process with the derived curve gives a relation between the second space derivative and the radius. From these two derived curves, then, the density may be computed according to equation (8).

Fig. 34 is a curve of the same type as curve 4 in Fig. 33*A*, and Fig. 35 shows the density as computed for the different values of *r*.

The density curve shows that which was deduced intuitively in regard to the changes necessary to produce the observed distortion of the field. The large resultant negative charge near the positive wire and the positive charge near the negative tube should be expected. A peculiar maximum appears about 2.7 cm. from the wire.

Sources of error are found in the potential assumed by a sphere in an ionized gas. It is difficult to draw conclusions concerning the absolute potential of a sphere in a conducting gas, since it is very likely that the potential at an undisturbed point in a gas is not the same as the potential assumed by a sphere when its center is at this point.

In a sphere near the positive electrode, the potential being initially the same as that of the gas, two streams of ions move in opposite directions past the side of the sphere, one containing a large number of negative ions and the other a smaller number of positive ions. The sphere intercepts more negative ions than positive so that its potential falls below that of the surrounding gas. The charge thus acquired by the sphere increases until the effect which it produces in attracting positive and repelling negative ions causes them to come in contact with the sphere in equal numbers. The final value of the potential assumed by the sphere is too high by an amount which depends upon the relative velocities of the positive and negative ions.

Conversely, when the exploring sphere is close to the negative electrode, there is a greater number of positive than negative ions intercepted so that the potential of the sphere rises above the potential of the undisturbed gas, until finally an equilibrium is reached. The number of positive charges acquired by the sphere is equal to the number of negative charges; thus the potential assumed by the sphere is greater than that of the undisturbed gas. If, however, the velocity of the positive ions is approximately equal to that of the negative ions, the exploring point should attain very nearly the same potential as that of the surrounding gas. For the pressures used in this series of experiments, the velocities of the ions are nearly the same. The error introduced could not, therefore, have been very great.

A slight error might be introduced if there were an appreciable voltmeter leakage between the point and the power line. The shape of the point also affects that of the potential curve to a small degree. The voltmeters used were practically free from leakage, and the work was done during cold, dry weather; so the error introduced from this cause is negligible.

CHAPTER VIII

THE PRESSURE INCREASE IN THE CORONA

Dr. S. P. Farwell was the first investigator to discover that at the instant the corona appeared on the wire the gas pressure in the corona tube increased. The increase appears very suddenly and also disappears very rapidly. For these reasons all the experimenters working in this laboratory have maintained that the pressure increase could not be due to heat. It has been suggested that it might possibly be due to ionization. This assumption is a possible consequence of the present theories of the corona, which assume it to be an ionization phenomenon. These theories assume that the high potential differences cause the few ions which are always present in a gas to move with a velocity sufficiently great to break the molecules with which they collide into two parts, one bearing a positive and one a negative charge. All these charged particles then move, because of the influence of the field, toward one or the other of the terminals. The presence of these ions thus explains the conductivity of the gas, and the acceleration of the ions explains the light effect. If the corona is an ionization phenomenon one would expect, provided the corona apparatus were enclosed, at the instant the corona appeared; i. e., at the instant the molecules were broken into ions, that the pressure in the apparatus would increase, because according to kinetic theory the greater the number of particles in a given volume the greater the pressure. Under certain circumstances the pressure increase can amount to as much as 3 cm. of mercury.

Professor Kunz (9), by theoretical considerations, has shown that this increase in pressure should be exactly proportional to the corona current.

Other investigators (10) have contended that the pressure increase could be completely accounted for as the result of Joule's heat and that the assumption that it is due to ionization is untenable. To support this contention Arnold performed experiments "by electrically heating the central wire in apparatus similar to Farwell's" and observed the pressure increase. With such an apparatus Arnold attempted to show: (1) that an increase in pressure due to heat ap-

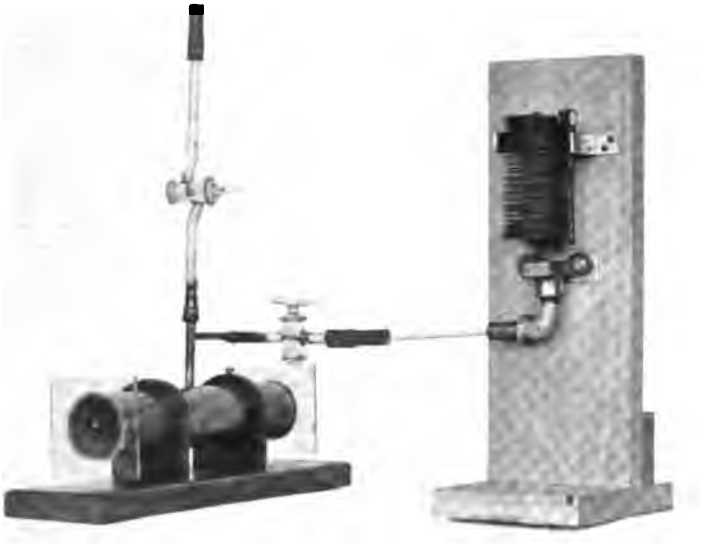


FIG. 36. APPARATUS FOR STUDY OF THE PRESSURE INCREASE IN THE CORONA TUBE

pears suddenly, and (2) that for a given power consumed in the tube the increase in pressure due to heat is of nearly "the same magnitude as those observed" in the corona.

In order to show clearly that the pressure increase is not due to heat a series of comparative experiments was performed with the pressure increase, caused (1) by producing the corona glow on the wire, and (2) by heating the central wire. The pressure increase observed in the first set of experiments will be referred to as *caused by corona* and in the second set as *caused by heat.* A few computations have also been made which strengthen the results of these experiments.

Since the conception of ionization is so intimately associated with the idea of increase in pressure, it seemed important to determine the laws relating to this sudden increase in pressure to the corona current.

24. *Apparatus.*—To the corona tube was soldered a small *T* tube, one side of which was joined to the vacuum pump and the other side was connected to a Bristol aneroid pressure gage (see Fig. 36).

The increase in pressure was measured by this Bristol gage. Any increase in pressure caused it to bend slightly and to rotate the mirror. When the deflection of a beam of light was seen over a scale,

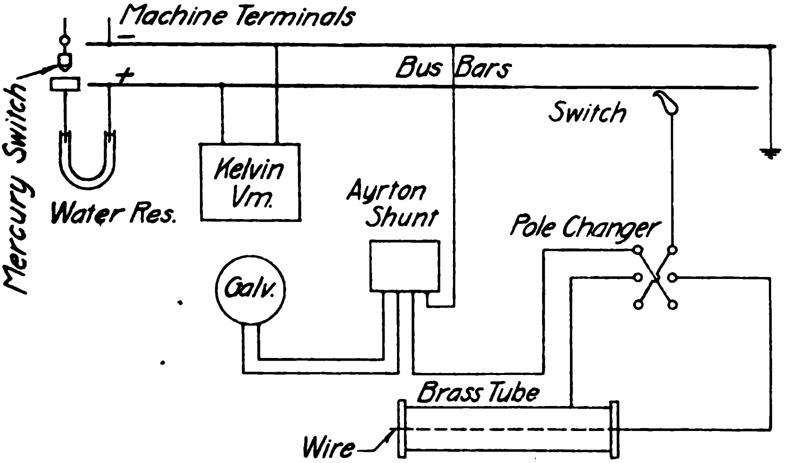


FIG. 37. DIAGRAM OF CONNECTIONS OF APPARATUS FOR THE DETERMINATION OF PRESSURE INCREASE IN THE CORONA TUBE

which had previously been calibrated by reading simultaneously the deflected beam and a water manometer connected directly to the gage, the increase in pressure in centimeters of water could be determined. The advantage of such a pressure measuring instrument in this experiment is its very quick action. The instant the pressure increases the gage jumps to its new position and a reading may be taken in a very few seconds. It was necessary to read this pressure increase quickly, because if much time was required the heating effect of the current would increase the pressure.

The current was measured by a Type *H* d'Arsonval galvanometer. The apparatus was connected as is shown in Fig. 37.

25. *Experimental Results.*—The results obtained from pressure increase in the corona were as follows:

(1) One who sees this pressure increase as recorded by a quick-acting pressure meter thinks it is not a heat effect, because of the rapidity with which it appears and disappears. Arnold showed that the pressure increase occurred very rapidly when caused by heat. The following curves show the difference in the rapidity in appear-

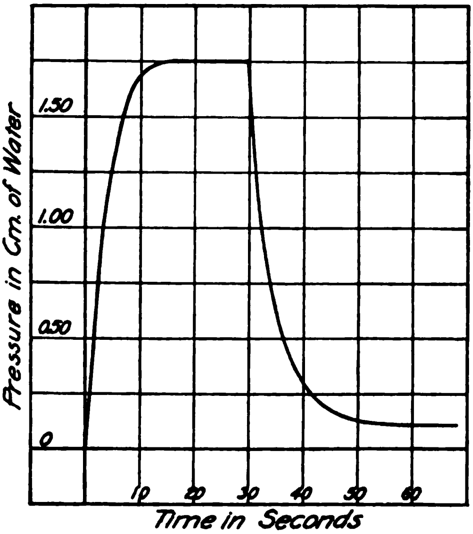


FIG. 38. PRESSURE INCREASE DUE TO HEAT

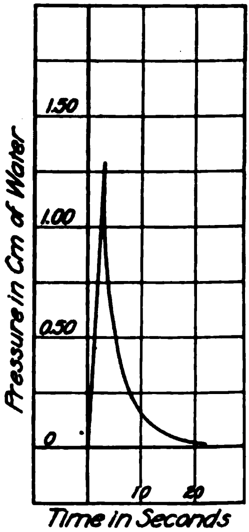


FIG. 39. PRESSURE INCREASE DUE TO CORONA

ance and disappearance of the pressure increase caused by heat and that caused by corona. It will be noticed in Fig. 38, where the pressure increase was caused by heating the central wire, that fifteen seconds were required for the pressure to come to its maximum value, and that from the time the current was broken twenty-five seconds were required for the pressure to return to practically its original value. In Fig. 39, however, where the pressure increase was caused by corona, only three seconds were required for the maximum pressure to be attained and the pressure came to practically its original value in eighteen seconds. In this last case from the appearance of the phenomenon, it seems, if the aneroid pressure meter had less inertia, that the pressure increase could be determined in less than three seconds. These curves show that the pressure increase appears five times as rapidly when caused by corona as when caused by heat and disappears also more rapidly.

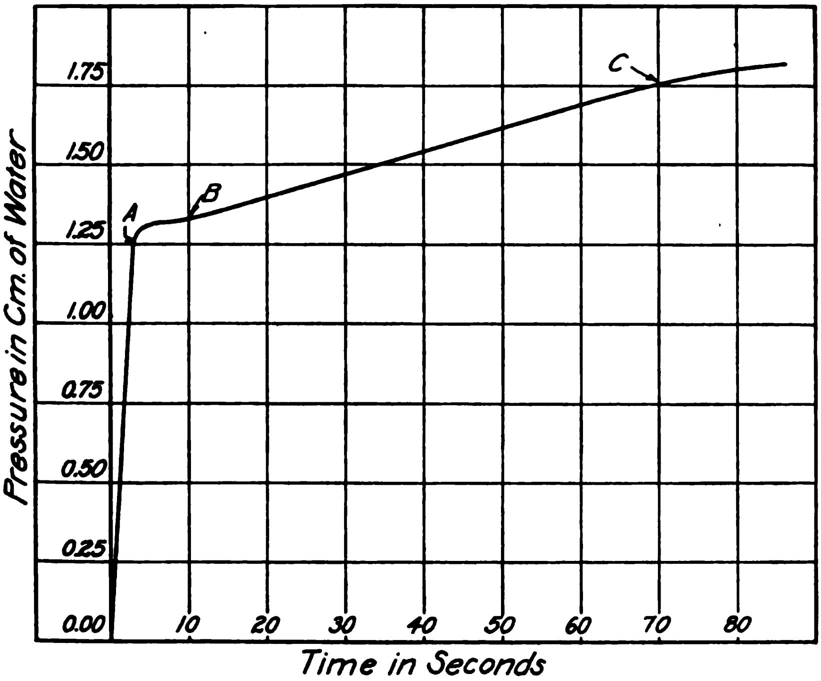


FIG. 40. PRESSURE INCREASE DUE TO CORONA AND HEAT

(2) In the pressure increase due to corona, a short time interval of five to seven seconds occurs after the sudden increase of pressure, before the heat effect in the corona begins to be noticed. This fact is shown in Fig. 40 by an abrupt bend, *a*, in the curve where the pressure increase is plotted against time. No such bend occurs where the pressure increase is caused by heat alone, as is shown in Fig. 38. In all the subsequent work the pressure increase measurements were always taken at a time corresponding to the point, *a*; by this means the heat effect is practically eliminated.

(3) The heat which is produced in the corona discharge, shown by the gradual pressure increase from *b* to *c*, Fig. 40, is distributed throughout the whole volume of enclosed air; consequently, when the circuit is broken, this heat does not radiate rapidly because the air is a poor conductor. This fact is shown very clearly in Fig. 41. The curve seems to show that the pressure increase due to heat in the corona is represented by the difference of ordinates of *c* and *b*, (Fig. 41). As soon as the circuit is broken at *c*, the increase in pressure due to corona at once disappears, but the increase in pressure due to heat in the corona discharge remains as is shown by the dif-

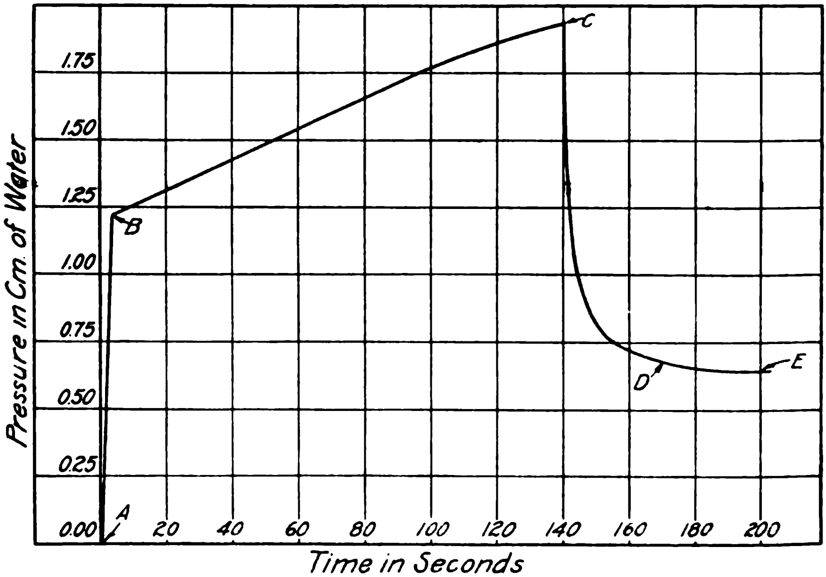


FIG. 41. PRESSURE INCREASE DUE TO CORONA AND HEAT

ference between ordinates *d* and *a*. This difference is always very nearly equal to the difference of ordinates of *c* and *b*. This heat energy produced by the corona current, since it is distributed through the gas, radiates very slowly, as is shown by the gradual descent of the curve from *d* to *e*. No such effect is observed when the increase of pressure is due entirely to heat, as is shown in Fig. 38. This curve shows that twenty-five seconds after the corona is removed from the wire the increase in pressure due to the corona has disappeared, but practically all the pressure increase due to heat in the corona (ordinate *c* minus ordinate *b* approximately equals ordinate *d* minus ordinate *a*) still remains and radiates very slowly.

(4) If the increase in pressure is due to heat, the same increase in pressure should result when the same power is consumed: (a) with a corona current through the gas and (b) with a heating current through the wire. Figs. 42 and 43 show that this is not the case. The powers consumed in the two cases are not exactly the same, but one can see that were they the same, the increase in pressure due to corona would be approximately half the increase in pressure due to heat. The power in the corona was obtained by multiplying the potential difference between the wire and the tube by the corona current, and in the heated wire the power was obtained by multiplying the current

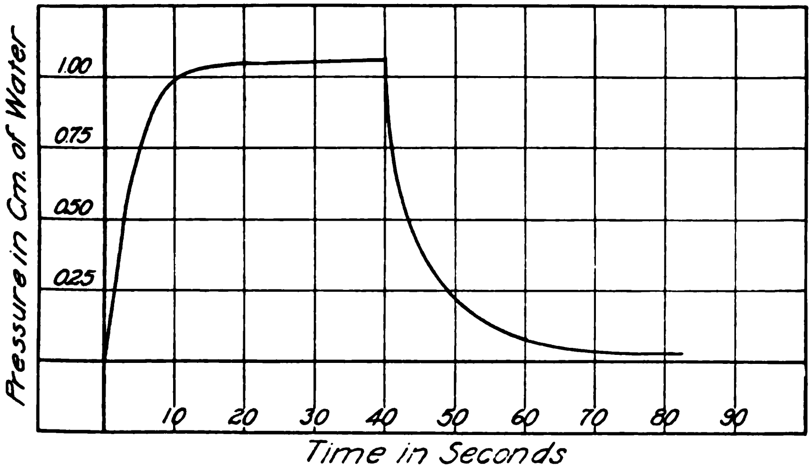


FIG. 42. PRESSURE INCREASE DUE TO HEAT. WATTS CONSUMED 0.238

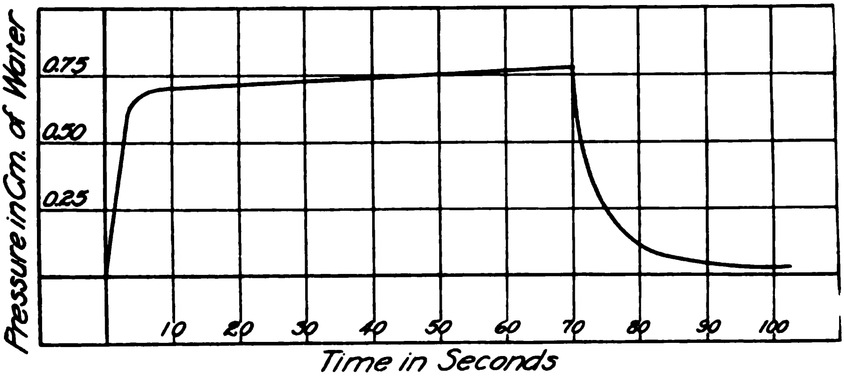


FIG. 43. PRESSURE INCREASE DUE TO CORONA. WATTS CONSUMED 0.266

through the wire by the potential difference across that portion of the wire which was in the tube.

(5) If the increase in pressure in the corona discharge is due to heat, the temperature of the air in the corona tube must increase. This condition may or may not be that of the luminous layer near the wire, but the temperature of the gas in the tube at a point four millimeters from the wire actually decreases. This decrease was determined by inserting a sensitive thermocouple made of very fine Copper-Advance wire into the corona tube. The temperature decreased only at the instant the corona appeared. In a short time after the heat due to the corona began to appear (corresponding to the slope *b* to *c*, Figs. 40 and 41) the temperature of the gas in the tube began to increase. This cooling effect is shown in Fig. 44. From a comparison of Fig. 44 with Fig. 40 it is seen that the increase in pressure which was measured at *a* was observed while there was an actual cooling in the corona tube. This cooling should be expected when air or oxygen is in the tube, for under these conditions ozone is formed. Since the formation of ozone from oxygen is always accompanied by an absorption of heat, the temperature of the air or oxygen would tend to lower. J. W. Davis, working on corona about hot wires in hydrogen, discovered that the appearance of the corona about a tungsten wire at white heat causes it to cool to dull red. This change tends to show that even in the corona glow itself there is a cooling effect. A possible explanation of the cooling effect might be given by assuming an electrical wind action around the conductor.

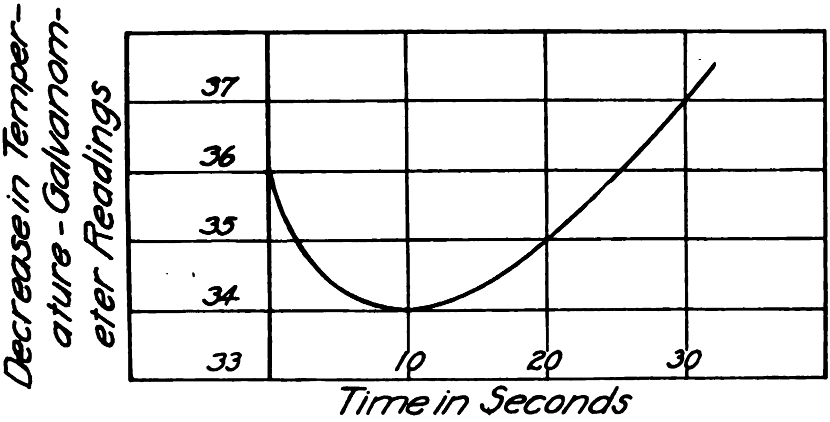


FIG. 44. COOLING EFFECT IN CORONA

(6) If the increase in pressure in the corona is due to heat, one should expect it to be the same with the wire either positive or negative. It will be mentioned hereinafter that it is impossible to obtain measurements when the wire is negative because of the presence of beads. The negative corona is entirely different from the positive corona.

(7) The following consideration will show, moreover, that the increase in pressure cannot be due to heat. The heat produced by the corona current will be given by the equation $H = 0.238\, eit$, and if the observed pressure increase is due to heat, the increase in pressure

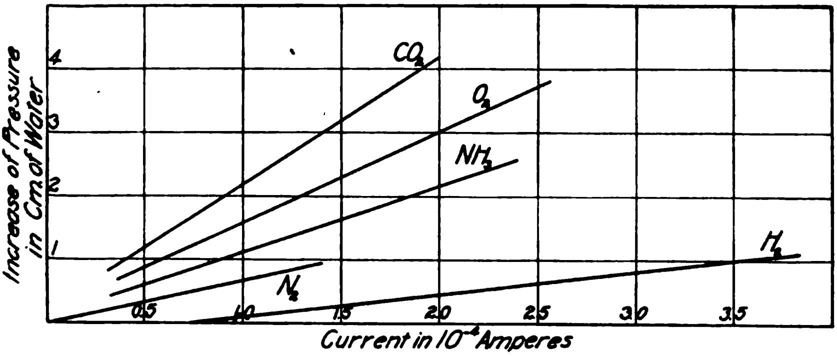


FIG. 45. RELATION BETWEEN IONIZATION PRESSURE AND CORONA CURRENT FOR DIFFERENT GASES

Δp will be proportional to the heat. The equation may then be written $\Delta p = k\ eit$. The only way for Δp to vary directly as i, the corona current, as shown by curves in the next paragraph, is for e to be independent of i. Data shows that this is not the case.

(8) To determine the laws relating this ionization pressure to the corona current, experiments were made when the wire was positive and the coaxial cylinder grounded with dry air, hydrogen, nitrogen, carbon dioxide, oxygen, and ammonia as the gases in the tubes. Considerable care was taken to see that these gases were absolutely pure. They were all dried carefully before they were used. Fig. 45 shows all the curves plotted to the same scale. With this scale the hydrogen curve should be continued until its ordinate is equal to that of the carbon dioxide curve.

The fact that the points all lie accurately on a straight line shows conclusively that the experiment verifies the prediction made by Dr. Kunz's theory. The law can then be stated that in the gases studied with the wire positive *the ionization pressure is exactly proportional to the corona current.*

In oxygen a considerable amount of ozone was formed because of the corona discharge. Evidently the curve as shown is a resultant of two effects: (1) A chemical change, due to the formation of ozone, which would tend to cause a decrease in pressure. (2) The increase in pressure due to the ionization of the oxygen. Since the ionization curve is a straight line, as is shown by the gases in which probably there is no chemical action, and since this resultant curve of oxygen is a straight line, the following law can be stated:

Whenever chemical change occurs because of the corona the chemical change is proportional to the current.

With the wire negative beads always appear, and since the pressure increase varies with the arrangement of the beads which are not stable, it is impossible to verify accurately the relationship. When an ordinary open manometer which is slow in its action was used instead of the quick acting gage, it was discovered that the same relationship as stated is very nearly true for the negative as well as for the positive wire.

The increase in pressure in nitrogen, showing ionization, is one of the exceptions where nitrogen is largely ionized at low temperatures and thus probably chemically active. How nitrogen, carbon dioxide, and ammonia are ionized are questions which require further study.

The arrangement of the apparatus could be used as a high potential voltmeter by simply calibrating the increase in pressure against volts, as determined by a disc electrometer.

26. *Results from Theoretical Considerations.*—If the increase in pressure is due to heat, it is possible to compute the magnitude of the pressure increase when one knows the watts of electrical energy consumed in the tube. The trial represented in Fig. 43 gives these data. The observed pressure increase was measured in three seconds so that the total number of joules of work consumed by the tube in that time was 3 x 0.266 = 0.798 joules. This amount corresponds to 0.1909 calories. Knowing the volume of the tube, the temperature and pressure of the air in it, one can readily compute the mass of the air in the tube. With the quantity of heat and mass of air mentioned previously, together with the specific heat of the air at constant volume, the temperature rise of the air can be computed, if the electrical energy is assumed to be converted into heat. This temperature rise is 2.44 degrees centigrade, which at constant volume corresponds to a pressure increase of nearly nine centimeters of water, while the observed pressure increase in this particular trial amounts to nearly seven-tenths centimeters of water. In this computation radiation and conduction losses have been neglected, because they would be very small from a body 2.44 degrees centigrade above room temperature. This computation shows that the observed results lie in a different order of magnitude from that expected if Arnold's theory were true.

Arnold states, if "we compute the corona currents that would result from the presence of enough ionized particles to produce the observed pressure changes, the currents calculated are many thousand times greater than those actually obtained." Such a statement is true only when the ionized particles are produced in a uniform or practically uniform electric field. This is not the case in the corona tube, as is shown in Chapter VII.

From these data it is seen that the potential gradient near the wire is very high, of the order of 30,000 volts per centimeter. This is the arcing gradient, in which probably every molecule is ionized. Then for a long space between the wire and the tube there is a very small gradient. With this condition of the field, every molecule may

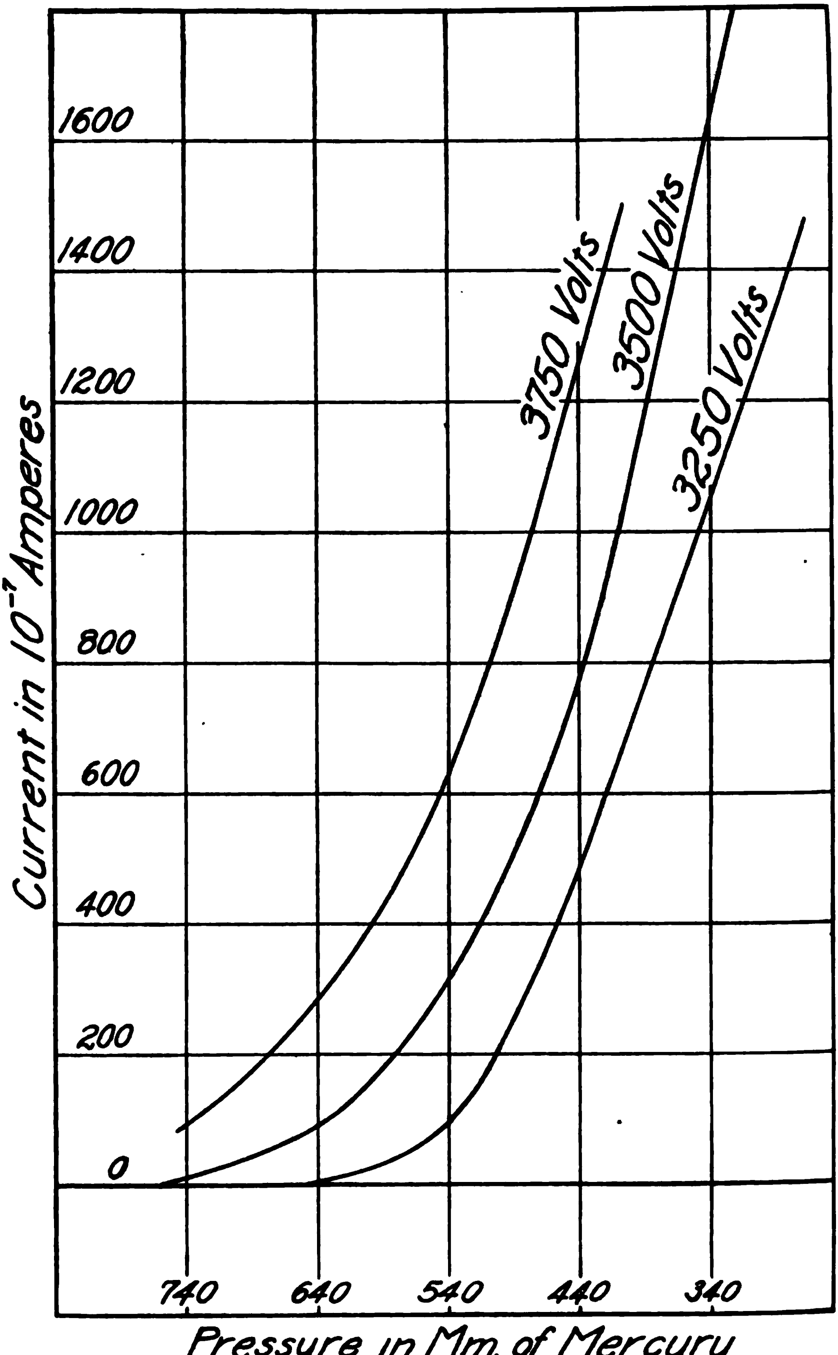


FIG. 46. CORONA CURRENT AS A FUNCTION OF PRESSURE IN HYDROGEN, WITH CONSTANT VOLTAGE AND WIRE POSITIVE

be ionized near the wire and still the resultant current be very small, for few of the ionized particles near the wire will pass through the space where there is a small gradient. Simple computations based on kinetic theory show that the maximum observed pressure increases can be explained by ionization if every molecule of the air within 1.39 millimeters of the wire is ionized. Within this distance the potential gradient is equal to the arcing gradient and it is therefore probable that all molecules are ionized.

27. *Further Verification of Kunz's Theory.*—The final equation as presented by Dr. Kunz is $ki = \frac{v_0}{e}(p_1 - p_0)\frac{1}{t} +$ a constant, where i is the corona current, v_0, the volume of the tube, e, the potential difference between the wire and the tube, $p_1 - p_0$, the pressure increase, k, a constant and p_0, the initial pressure. This equation shows that for a constant potential difference, e, the current, i, should increase as p_0 is lowered. Data were taken by measuring the current at various measured pressures, caused by a constant potential difference, which verifies this theory. These data are shown graphically in Figs. 46 and 47 when pure hydrogen and nitrogen respectively were the gases in the tube.

28. *Summary and Conclusions.*—Experimental results show:

(1) That the increase in pressure due to the corona appears and disappears much more rapidly than when due to heat only.

(2) That the heat in the corona discharge is not a prominent factor until many seconds after the corona appears.

(3) That in equal energy experiments the increase in pressure due to corona differs from the increase in pressure due to heat by nearly 50 per cent.

(4) That at the instant the corona appears the gas in the tube at a small distance from the wire is cooled.

(5) The ionization pressure in the positive corona is exactly proportional to the corona current in dry air, hydrogen, nitrogen, carbon dioxide, oxygen, and ammonia.

(6) Any chemical action that occurs because of the corona is proportional to the corona current.

(7) That the theory advanced by Professor Kunz is verified in one more field; namely, in the relation between current and pressure for constant voltage.

These results together with conclusions drawn from simple calculations force one to believe that the pressure increase in the corona

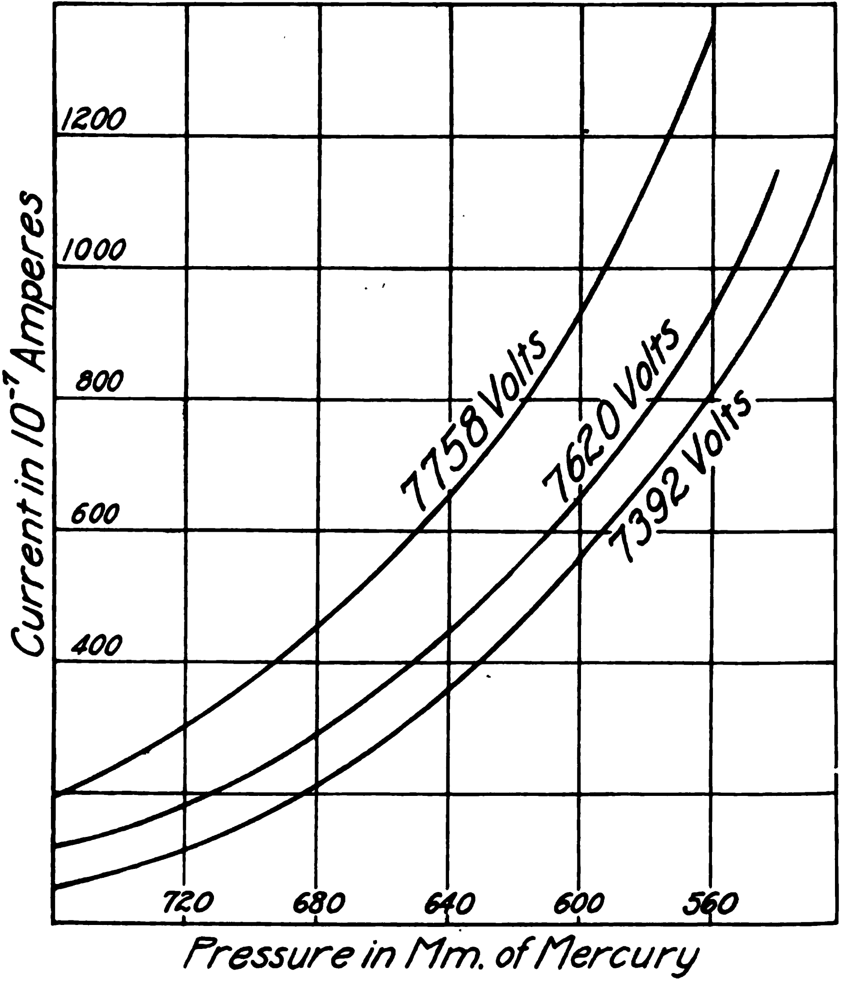


Fig. 47. Corona Current as a Function of Pressure in Nitrogen, with Constant Voltage and Wire Positive

discharge is not due to Joule's heat. With the knowledge of the distortion of the field in the corona tube it seems very possible that the increase in pressure is due to ionization.

Dr. A. M. Tyndall has also argued against a characteristic pressure effect in the corona. In his experiments he used a much smaller tube and introduced about one thousand times more energy per unit time than that used in these experiments, unless there is a misprint in the current (10^{-6} instead of 10^{-3}). Even if there were a misprint, the relative energy is still larger in Tyndall's experiments, because his inner wire was about thirty times smaller than those used in the measurements herein recorded. It is therefore possible that Tyndall observed only heat phenomena; moreover from his data it cannot be concluded that the pressure increase in question is proportional to the corona current, a fact which requires an explanation different from a simple heat effect. The cooling of the wire by the corona had been discovered in the Physics Laboratory of the University of Illinois before Tyndall published his paper. Tyndall's experiments cannot be considered conclusive; the characteristic pressure measured by Warner may be due to an increase in particles or to a partial vacuum surrounding the wire when the corona discharge takes place. The problem is not yet solved.

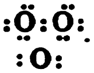
CHAPTER IX

OZONE FORMATION IN THE CORONA

Among the problems attracting attention at the present time, that of the nature of the forces which hold the atoms together in the molecule is of great importance. The most probable suggestion is that these forces are due to the electrons and positive nuclei of the different atoms acting on each other according to laws still obscure. Most of the articles which have been published concerning this problem are of a speculative nature. If the forces are electrical, it seems obvious that some electrical method might be used advantageously in their study. Ionization, often followed by chemical reaction, is found to occur in solutions of electrolytes and sometimes in gases. A tremendous amount of work has been done with electrolytes in solutions of various solvents. These studies have led to the development of many interesting relationships, but there are so many complications in any study of liquid solutions that it is difficult to get much conception of the fundamental intramolecular forces. In spite of the fact that a much greater amount of work has been done on ions in solutions than on gaseous ions, more is known about the latter. In gases the ions have greater freedom of movement than in liquids. The structure is simpler and it is much easier to control and alter conditions. Ionized gases with charged atoms and molecules are often capable of causing chemical action and so may well lend themselves to the study of those forces which bind the atoms together. To cause a reversible reaction like $N_2 + O_2 \leftrightarrows 2NO$, for instance, to shift toward the right by purely thermal means would require a very high temperature for appreciable yields, but with the ionization of gases resulting from various forms of electrical discharge, similar yields can be secured at far lower temperatures. It seems probable, then, that the presence of ions in gases is the cause of new combinations of the atoms, but it might be that ionization is only an accompanying effect, not the cause of chemical reactions. It is very desirable when studying fundamental relationships to work with conditions as little complicated as possible. For this purpose there is available one reaction that involves the presence of only one element, oxygen, which is changed into ozone under suitable conditions.

The following is a discussion of the theory of ozone formation which is applied to the various known types of ozone formation: the oxygen atom is supposed to possess six electrons in the outer shell. The two atoms in the molecule may be held together in two different ways, between which there may be several gradations. The oxygen molecule may be represented by either of the formulas A, $:\ddot{\mathrm{O}}:\ :\ddot{\mathrm{O}}:$ or B, $:\underset{\cdot}{\ddot{\mathrm{O}}}:\underset{\cdot}{\ddot{\mathrm{O}}}:$. In the first form the atoms are held together by two valence bonds while in the second there is only one bond, each atom possessing an extra, unsatisfied valence. It is supposed that a valence bond is due to the coupling together of two electrons which tend to make a fairly stable union. In form B each atom has an extra unbalanced electron, and an arrangement exists similar to the usual conception of the ethylene molecule. In its second form the oxygen molecule would be highly reactive as, indeed, oxygen is well known to be.

If a neutral oxygen atom came in contact with form B, there would be a strong tendency to form the neutral molecule of ozone,



$$\begin{array}{c} :\underset{\cdot\cdot}{\ddot{\mathrm{O}}}:\underset{\cdot\cdot}{\ddot{\mathrm{O}}}: \\ :\mathrm{O}: \end{array}.$$

The electrons not being symmetrically placed about the nuclei a strain results so that ozone is in an unstable condition and readily tends to decompose. The heat of decomposition of ozone by direct measurement is about +34,000 calories. This value is the resultant of the force required to split two extra atoms from two ozone molecules and of the force with which these two atoms unite to form a molecule, regardless of the order in which these steps may occur. It seems likely that an atom would have to come in contact with the unsaturated form of molecule B at just the right angle and with a suitable velocity in order to produce ozone. Collision between two atoms would result in the formation of a molecule with consequent degradation of energy as heat.

Apparently the formation of ozone requires oxygen atoms which may be derived from molecular oxygen or from some compound of oxygen with other elements. On this basis, in accordance with the mass-action principle, any factor which increases the atomic oxygen concentration ought to raise the yield of ozone.

Ozone is formed in many chemical reactions. The practical method for the manufacture of ozone is to pass air through some form of silent discharge. Whenever ozone is formed by means of an electrical discharge, light is produced. Indeed ultraviolet light of sufficiently short wave length produces ozone. It is possible that it is the light which produces the ozone even in the silent discharge and in the corona discharge. The vibrations of the ultraviolet light tend to loosen the oxygen bonds, to produce polarization at first and finally to cause dissociation of the atoms analogous to the thermol action of high temperatures.

The formation of ozone is an end of thermic reaction. At ordinary temperature ozone decomposes into oxygen, but the rate of decomposition is slow. The velocity of decomposition increases very rapidly with increasing temperature, so that for practical manufacture of ozone the gas should be as cold as possible.

For the formaton of ozone atomic oxygen seems to be required; the atoms may or may not be changed and this is a very important question.

The chemical reaction may be written in the form $O_2 - O \rightleftarrows O_3$. The heat of decomposition of ozone is about 34,000 calories. Ozone is, therefore, in a metastable condition at ordinary temperatures.

For the ozone formation in the corona discharge the following method and arrangement were chosen. The oxygen was prepared by electrolyzing a 20 per cent solution of sodium hydroxide with nickel electrodes. To remove hydrogen the gas was passed over heated copper oxide. Any carbon dioxide was removed by a 20 per cent sodium hydroxide solution in a bead tower. The gas was dried

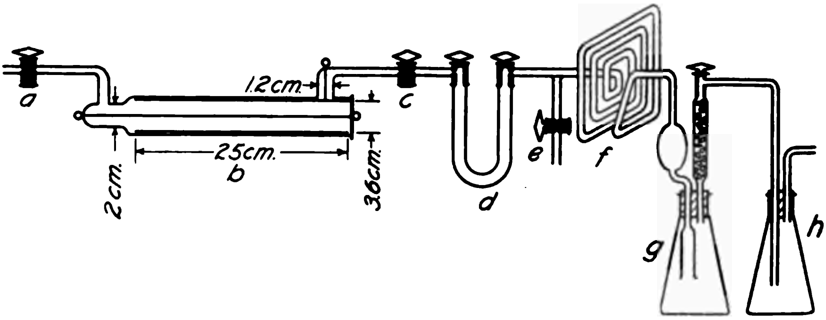


Fig. 48. Diagram of Apparatus for the Study of Ozone Formation in the Corona

by being passed through another bead tower containing concentrated sulphuric acid, through a large U tube filled with pieces of fused potassium hydroxide and finally through another large U tube full of phosphorous pentoxide. The corona tube was of glass; its dimensions are given in Fig. 48. The outer electrode was a sheet of gold foil 0.15 mm. thick. Connection was made by a platinum wire sealed through the glass and passing all around between the foil and the glass tube. A slit was left in the foil so that the discharge might be observed. It had the characteristic appearance for this form of discharge as described previously in this bulletin. The procedure was to fill the tube with pure oxygen, close the stopcocks and subject the enclosed volume of air to the discharge for varying lengths of time. The gas was then passed through neutral 2 N potassium iodide. The iodine set free was titrated with 0.025 N thiosulphate solution after acidifying with sulphuric acid. During the discharge the current strength was measured by a suitable galvonometer and was main-

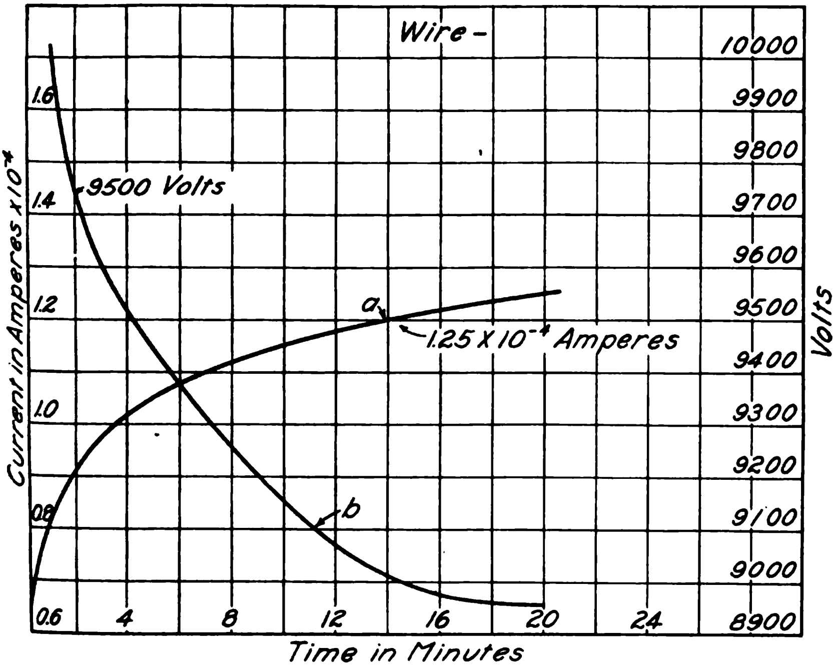


FIG. 49. INCREASE OF VOLTAGE AT CONSTANT CURRENT AND DECREASE OF CURRENT AT CONSTANT VOLTAGE IN THE FORMATION OF OZONE IN THE CORONA

tained constant by increasing the voltage as required. The resistance of the gas rises with the length of time of the discharge. The required increase in voltage due to the increased resistance is an exponential function of the time

$$V_t = V_0 e^{at}$$

V_0 is the initial voltage, V_t is the voltage at any time t, and a is some constant. This relation is well illustrated in Fig. 49, curve *a*. On the other hand if the voltage is maintained constant, the current strength will decrease as in Fig. 49, curve *b*. The formula for this hyperbolic curve will be somewhat like the other formula but with a negative exponent. An explanation of this phenomenon is given later. The state of affairs in the discharge is somewhat complicated. When the current is turned on, there is a slight immediate rise in pressure due to the ionization of the gas. This increase in pressure means a splitting of the molecules into atoms so that the total number of particles in the gas is increased. The oxygen atoms formed in oxygen unite chiefly with oxygen molecules to form oxone with a consequent decrease in volume which may be followed by a suitable manometer. The most (90–97 per cent) of even the initial energy is degraded into heat energy. As the ozone increases in concentration more of it decomposes with the liberation of more heat. All this heat causes an increase in the velocity of the molecules and an increase in the volume of the gas. The decrease in volume, which is a resultant of the ozone and heating effects, should bring about a decrease in resistance. The increased velocity of the molecules should also help to lower the resistance. Both of these effects should allow the easier passage of the ions through the gas. The explanation of the increase in the resistance is the counter electromotive force or polari-

TABLE 5

CURRENT-VOLTAGE RELATIONSHIP

Wire Positive		Wire Negative	
Amperes $\times 10^{-4}$	Volts	Amperes $\times 10^{-4}$	Volts
2.00	7910– 8300	1.25	8960–9550[1]
2.77	8960– 9260	2.50	9880–10280
3.75	9370– 9650	3.75	10400–10600
6.25	9680–10440	5.00	10800–11240
		7.50	11600–12480

[1] Cf. Fig. 49, Curve *a*

zation effect exerted by the ions present. As long as the tube is closed its size is the limiting factor. After a condition of equilibrium is once reached throughout the tube, the voltage required to maintain a certain amperage should be constant. The ionic equilibrium like the ozone-oxygen equilibrium depends upon diffusion to a large extent and this in turn is governed by the size and shape of the tube.

These data are the extreme values observed during a 20-minute run. To test the reproducibility of the method, runs were made during two different days with all the conditions as nearly constant as possible. Each run lasted just three minutes. The current strength was maintained exactly at 2.77×10^{-4} amperes and the wire was posi-

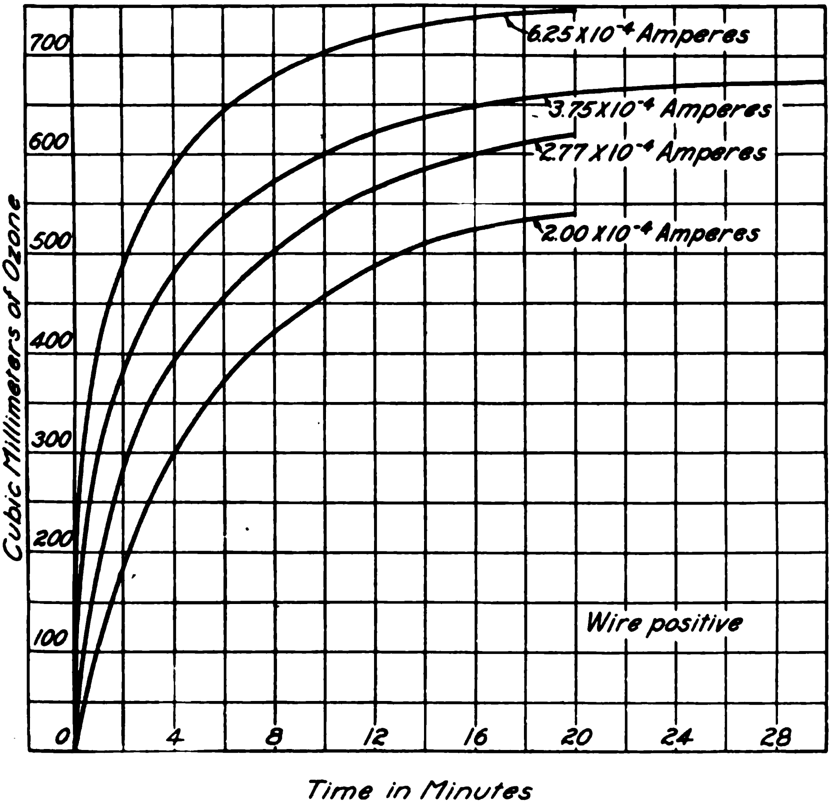


FIG. 50. OZONE FORMATION IN THE CORONA TUBE AT VARIOUS CURRENT STRENGTHS WITH WIRE POSITIVE

tively charged. The results were 345, 340, 335, and 360 cu. mm. of ozone. This corresponds to nearly 6 g. per kw. hr., a value lower than the values given hereinafter; for here the deozonizing effect of the discharge is considerable. To calculate the yield in terms of percentage divide the value in terms of cubic millimeters by 3000.* The results plotted in Figs. 50 and 51 represent all the results obtained with the amperage at a constant value and with no arc in series. The following yields have been calculated from measurements of the initial slopes of these curves.

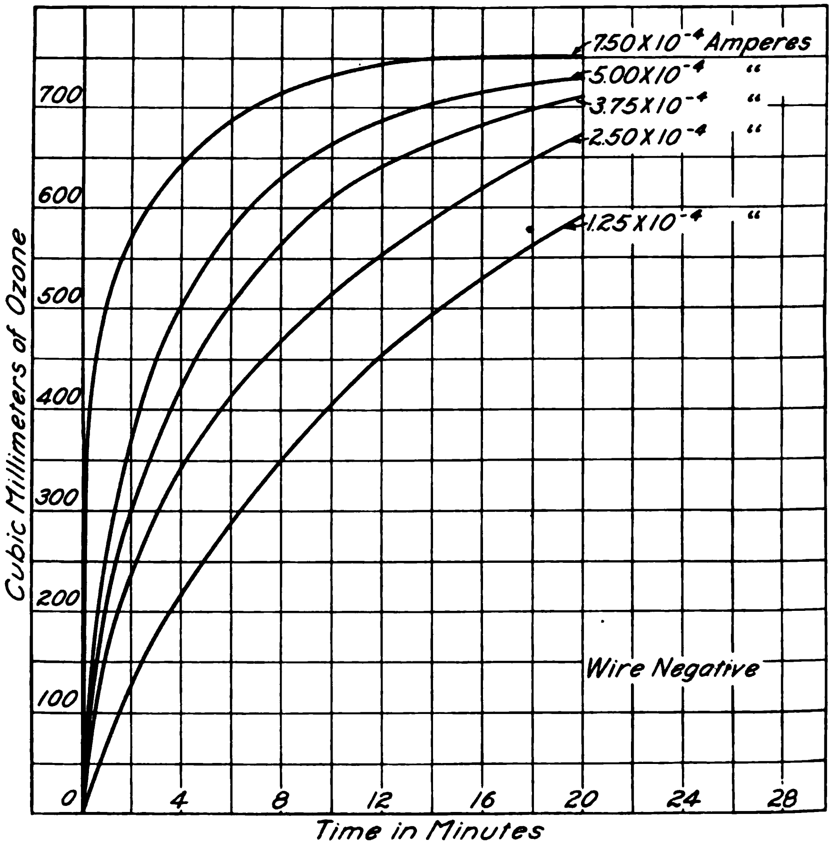


FIG. 51. OZONE FORMATION IN THE CORONA TUBE AT VARIOUS CURRENT STRENGTHS WITH WIRE NEGATIVE

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* The capacity of the tube being 300 cc. to change from cubic millimeters to percentage multiply by 100 (300 × 1000) or divide by 3000.

TABLE 6

OZONE YIELDS CALCULATED FROM THE INITIAL SLOPES OF THE CURVES IN FIGS. 50 AND 51

Wire Positive Grams of Ozone per Kilowatt Hour			Wire Negative Grams of Ozone per Kilowatt Hour		
Amp. $\times 10^{-4}$	Without Spark	With Spark	Amp. $\times 10^{-4}$	Without Spark	With Spark
2.00	7.7	13	1.25	13	22
2.77	12.7	18	2.50	14.1	23
3.75	20.7	29	3.75	14.2	25
6.25	23.3	..	5.00	11.3	..
....	....	..	7.50	24	..

These values are being checked by passing the gas through the discharge at various speeds. With the wire charged positively, about the same amount of ozone is formed as with the wire charged negatively. This result does not agree with either Warburg* or Cermak† who working with a point discharge and influence machine current observed the ozone concentration with the point negative to be about three times the concentration when the point was charged positively. Their explanation was that the greater speed of the negative ions was responsible. This seems to be a reasonable explanation, but these curves show that there is something more to be taken into consideration. The point discharge, especially with an influence machine supplying the current, is very complicated. The curves in Figs. 50 and 51 belong to a family of parabolic curves which tend to approach a common point as a limit. The general formula for these curves is,

$$y = a\,t^{n}$$

where y is the yield of ozone, a is a constant, t is the time, and n is a fraction between 0 and 1. The greater initial slope of the larger current curves indicates that there is a greater ozonization, but the smaller slopes of these curves after five minutes show that there is also a very much larger deozonizing effect. The resultant is probably the same in all cases with an electrical equilibrium formed. This electrical equilibrium for any one apparatus and source of power is probably independent of the current strength. It is the resultant of the ozonizing and deozonizing effects of the current and the small spontaneous decomposition of ozone at the temperatures (24 ± 3 degrees) and pressures (740 ± 5 mm.) used.

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* Ann. Phys., Vol. [4] 9, p. 781, 1902.

† Ber. deut. physik. Ges., Vol. 4, p. 268, 1906.

A few experiments were made with a spark gap in series. The spark was between two 1 cm. zinc spheres which were adjusted by a micrometer screw. The effect of an arc in series with the corona has been studied by Crooker.* He showed that the effect is not to produce an oscillating but an intermittent direct current. In Table 6 some yields are given of ozone per kilowatt hour. These were calculated as follows: With the wire positive and with the current of 2.00×10^{-4} ampere, the yield of ozone was two-thirds greater for the three-minute interval with rather than without the spark in series. The increases are greater for the smaller current strengths. These results throw some light on the effect of alternating or fluctuating current and of different frequencies on ozone production. This point will be discussed later in connection with the further study of ozone formation in the corona which is being continued in the Chemical Laboratory of Purdue University.

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*Crooker, Am. J. Sci., Vol. 45, p. 281, 1918.

CHAPTER X

THE INFLUENCE OF A SERIES SPARK ON THE CORONA

The typical positive corona discharge is a uniform glow around the wire, while the negative corona consists in more or less evenly spaced bright beads. If a short spark is included in series with the corona tube, this difference in the discharge is largely eliminated, the discharge appearing almost the same whether the wire is positive or negative. The introduction of the spark in series entirely changes the visual character of the corona glow. The usual characteristic negative beads spread laterally and in diameter into a fuzzy glow (blue in air), whereas the quiet uniform positive glow gives place to a remarkable display of purple streamers shooting radially from the wire to the tube and at times completely filling the tube with light. These visual characteristics are essentially the same in all gases.

When this marked difference between the corona with and without the spark in series was first discovered, it was suggested that perhaps this difference was due to high frequency oscillations super-

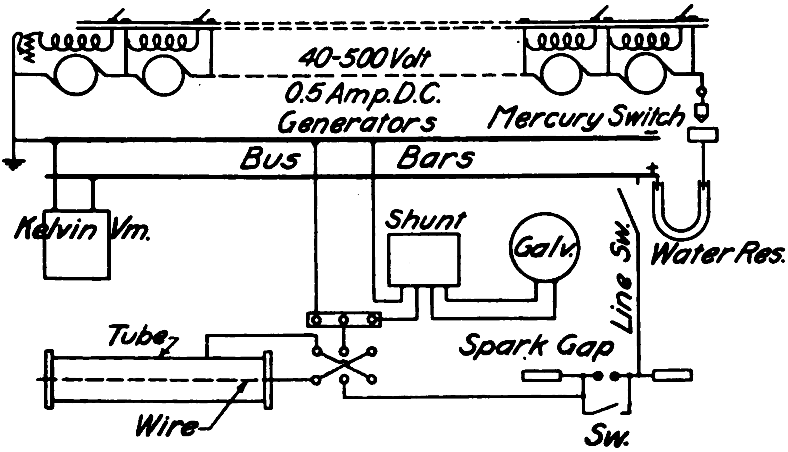


FIG. 52. DIAGRAM OF CONNECTIONS OF APPARATUS FOR STUDY OF INFLUENCE OF A SERIES SPARK ON THE CORONA

imposed upon the direct-current phenomenon. The results presented in the following pages of this chapter comprise the present knowledge of this peculiar corona phenomenon.

29. *Apparatus.*—The electrodes of the spark gap were polished brass spheres, one centimeter in diameter, fastened to brass rods which were supported by hard rubber blocks on a solid hard rubber base. One of the electrodes was supplied with a micrometer screw and an insulated handle which permitted an easy adjustment of the spark discharge. This spark gap was connected in series with the self-opening line switch and the corona tube through a reversing switch which allowed quick reversal of the polarity of the axial wire. The connections of the apparatus are shown in Fig. 52.

30. *Visual Characteristics of the Corona with Spark in Series.*—If in positive corona a short spark is placed in series with the corona tube, containing air at atmospheric pressure, after the voltage is high enough to give a bright uniform glow a most remarkable change takes place in the discharge. For very short sparks a few bright purple radial pencils or streamers of light will shoot out irregularly from the wire toward the tube. These streamers increase in number and in brightness as the spark gap is opened and may at times completely fill the tube with purple light. They are brighter and more easily formed at the higher pressures and at voltages slightly above that for the starting glow, but they have been observed at pressures as low as 30 cm. of mercury.

The same changes in the appearance of the positive glow by the introduction of a series spark have been observed in illuminating gas and hydrogen. The uniform positive glow is in both cases transformed into the radial streamers by the action of the spark. In illuminating gas these streamers are of an intense blue-green color, while in hydrogen they are of a milky white or silvery appearance.

In negative corona a short series spark has the effect of destroying the characteristic negative beads. Introducing a very short spark reduces the clear beads in brightness and in their clear-cut form, and they become hazy at the boundaries. Gradually opening the spark gap causes a slow transition of the beads from the clear intensely concentrated form of glow to a uniform fuzzy glow which spreads laterally from the beads along the wire and which is slightly larger

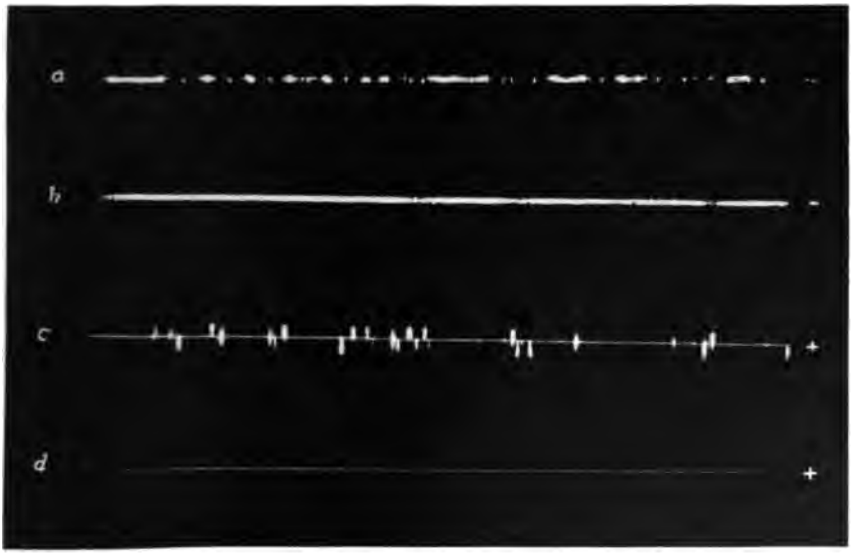


FIG. 53. CORONA DISCHARGE WITH AND WITHOUT A SERIES SPARK

in diameter than the original beads. The bright cores of the beads maintain their positions until the last, although they are greatly reduced in intensity and may even be seen when the spark gap is so long that the glow flashes but intermittently. The characteristic destruction of the clear form of the beads due to the action of the spark has also been observed in illuminating gas and in hydrogen at various pressures. The appearance of the glow remains the same, whether the spark is placed on the grounded side of the tube or on the high potential side.

Photographs of the corona discharge with and without a series spark are shown in Fig. 53.

31. *No Oscillations in the Corona.*—When the influence of the series spark was first discovered, the action was attributed to oscillations or surges started in the system by the spark. This suggestion was made, because when a 2 micro farad condenser was placed in parallel with the tube and the wire, the hazy, beaded discharge appeared for both positive and negative corona, and did not change in character when a series spark was added to the circuit. When the spark is placed in series many times, a hissing sound is heard which might be due to oscillations.

To determine whether the series spark sets up oscillation several experiments have been performed. The results, which show that oscillations are not present, will be given in the following paragraphs.

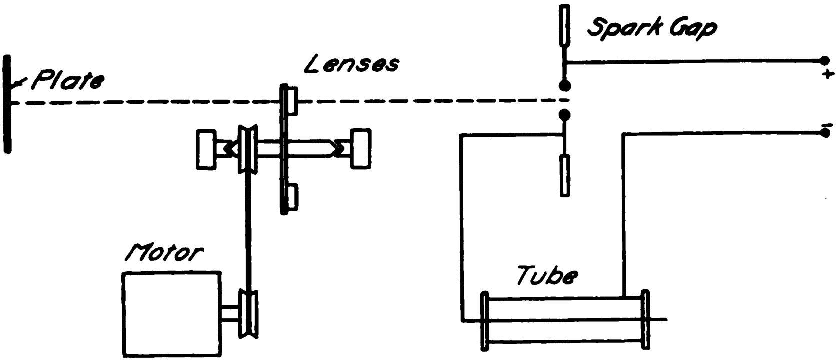


FIG. 54. ARRANGEMENT OF APPARATUS FOR BOYS'S METHOD

The difference between the positive and negative corona with series spark, as described, is so conspicuous as to exclude the possibility of the effect being due to oscillations. If there were oscillations, they could not be symmetrical with respect to the time axis.

The oscillograph and vibration galvanometer cannot be used to determine the current wave form, because the currents are too weak to overcome the inertia of the moving elements. Three methods have been used which give accordant results: the telephone, revolving lenses and a photographic plate, and a cathode tube with a hot lime cathode. The last method may be made very sensitive and gives satisfactory results.

In the telephone receiver method a receiver connected in parallel with a resistance was used in place of the galvanometer. The passage of the faintest spark can be detected. When the voltage is high enough to produce corona, a sharp click is heard in the telephone as each consecutive spark passes and a flash of glow appears on the wire in the tube. If the sparks pass in very rapid succession, the glow will appear to be practically continuous. The discharge between the spheres is intermittent and forms a white line in the gas.

The corona tube acts like a condenser charging and discharging at intervals, according to the length of the spark gap. It can be arranged so that for long sparks only one spark passes per second or for short sparks several thousand pass per second, and as each spark passes it will register a sharp click in the telephone receiver. Decreasing the spark length from the longest sparking distance will make the sparks jump faster and faster until for very short spark lengths the sound in the telephone practically passes from the audible range. The results obtained with the telephone suggest the assumption that the corona current with a spark in series is only intermittent and not oscillatory.

Boys's method consists in photographing the spark directly when the image from it sweeps across a photographic plate. Boys (19) used a system of six revolving lenses set in one solid disc. Each lens was mounted a little offset from the center of the disc as compared with those adjacent, so that the image from it would not overlap the others. The arrangement of the apparatus is shown in Fig. 54. All the lenses have the same focal length; so the spark gap can be focused on the plate through any one of them. The spark gap and the photographic plate are stationary, but since the lenses move, the

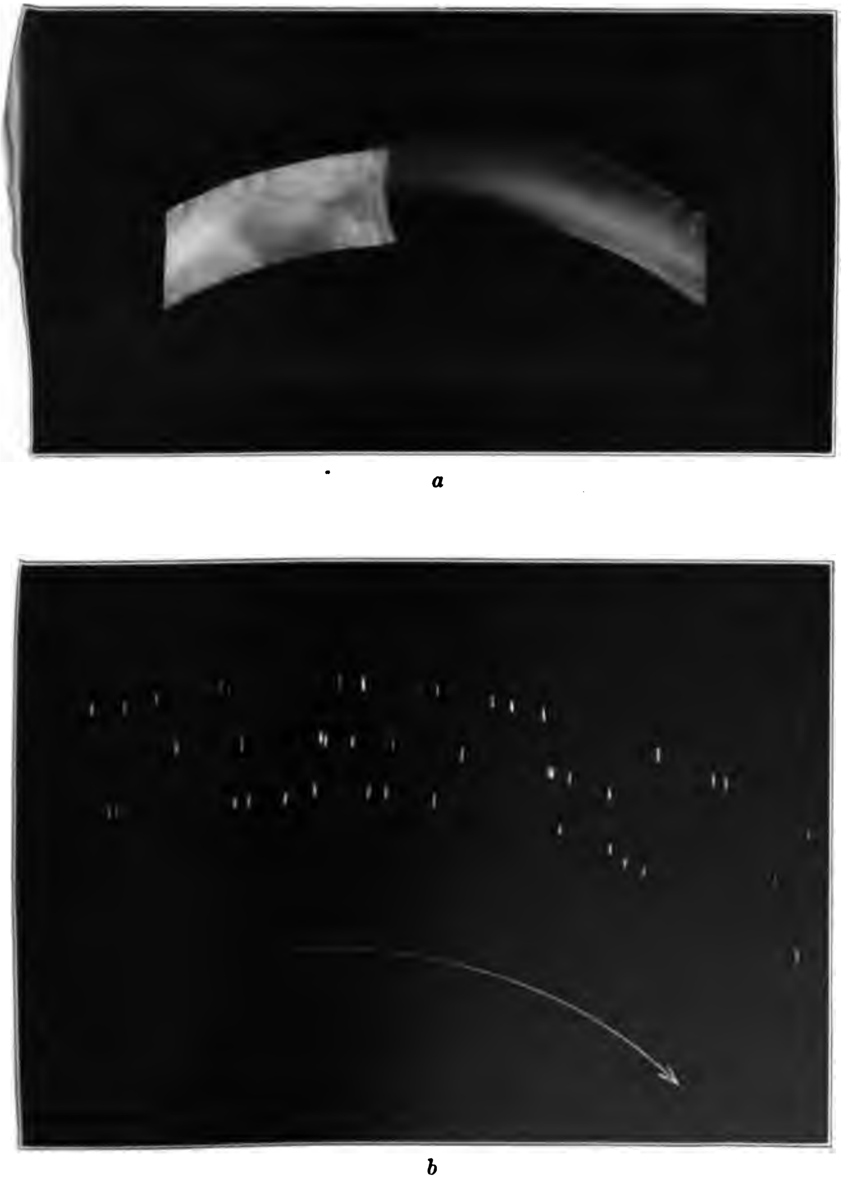


Fig. 55. Photographs of Oscillatory and Unidirectional Sparks

focus of the spark shifts from one point to another across the plate leaving its record of instantaneous images.

A small motor drives the lenses at a speed of about 6000 r. p. m. The lenses are set about four inches from the center of the disc so that it is possible to get a linear speed of approximately 100 ft. per sec. across the face of the photographic plate.

By this method it is possible to analyze the spark and to determine whether it is of an oscillatory or unidirectional character. An oscillatory spark will give an irregular band of light across the plate (see Fig. 55*A*), while a unidirectional spark leaves only a sharp line (see lines in Fig. 55*B*).

For rough determinations it is easy to observe the image of the spark on the ground glass plate and to find quickly if the spark is oscillatory or not. If it is oscillatory, one can observe the approximate frequency and duration of the spark. For more nearly accurate determinations photographs must be made on sensitive plates and observations and measurements made from them.

Several observations were made with this method for various spark lengths and speed of lenses using both air and hydrogen in the corona tube. In the first experiment corona was produced in air at a pressure of 500 mm. by a potential of 14,000 volts. The spark gap was about 1.5 mm. in length and the lenses were driven at a speed of 2,000 r. p. m. A photograph was taken, but the individual sparks showed no trace of being oscillatory.

To spread out the individual spark images the lenses were driven at the higher speed of 6,000 r.p.m. and the spark gap set at 1.19 mm. This arrangement allowed a passage of nearly 2,500 sparks per second and a speed of about 100 ft. per sec. across the plate. The half-tone, Fig. 55B, clearly showed that the sparks were not of an oscillatory character but unidirectional, that only a sharp line was recorded as each spark passed, and that the duration was less than 1-100,000 second. Each spark was, moreover, a little brighter at the negative electrode, and showed that all the sparks passed in the same direction and were of the same character.

With hydrogen in the tube at a pressure of 744 mm. and a potential of 9,400 volts photographs were taken when the spark gap was 0.75 mm. and 0.3 mm in length. For the 0.75 mm. gap the frequency of the sparks was about 10 per second and produced a large number of silvery streamers in the corona tube. When the gap was reduced to 0.3 mm., several hundred sparks passed per second and the corona tube was completely filled with streamers. In every case the sparks were unidirectional, sharp and clear-cut, and showed no oscillatory character whatever.

To determine the form of the current curves when the spark is in series a special hot-lime-cathode Braun tube was designed and constructed as shown in Fig. 56.

A narrow platinum strip, *P*, fastened to the insulated brass blocks, B_1B_2, is heated by an auxiliary current passing through the leading-in conductors, C_1C_2. A small spot of calcium oxide placed upon this heated strip has a peculiar property of giving off a stream

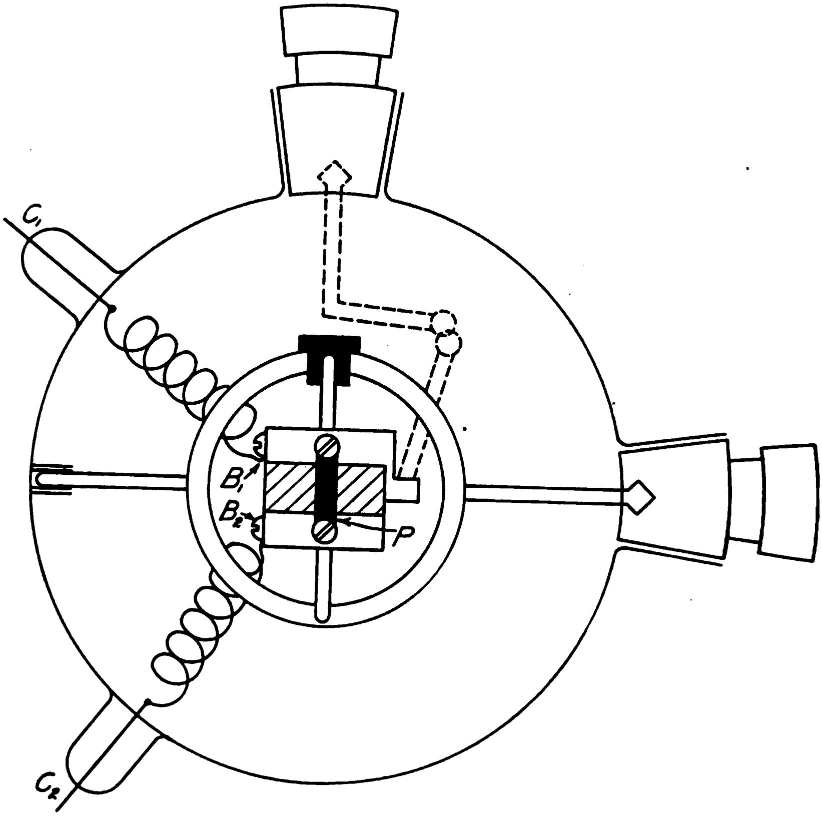


FIG. 56. THE ADJUSTABLE HOT-LIME CATHODE

of slow moving electrons when used as cathode in a discharge tube at a very low pressure. It is necessary to use only a low potential of nearly 400 volts between anode *A* and cathode *C*. The block holding the platinum strip was mounted upon a gimbal support, as shown, in order that the soft cathode beam could be easily adjusted through a hole in the diaphragm, *D,* fall upon the fluorescent screen, *S,* and there produce a spot of maximum brightness. This double adjustment is necessary, for it is impossible to assure by construction the exact direction of the beam.

If a very weak magnetic field is placed at right angles to this beam of slow moving electrons, the beam will be deflected and the bright spot shifted on the fluorescent screen. When the magnetic field is alternating or pulsating, the rapidly moving spot will cause a line to be seen on the screen. If this line is observed in a mirror rotating at right angles to it, the line is spread out into a curve representing the variations in the current of the coil which excites the magnetic field.

The coil used had about 3,000 turns of No. 26 enameled copper wire wound in two sections and mounted so that it could be fitted closely to the neck of the tube.

It might be advantageous to note briefly some of the details necessary in constructing and operating the hot-lime-cathode Braun tube.

(1) The cathode should be adjustable in order to get a spot of maximum brightness.

(2) A diaphragm, D, is necessary to eliminate extraneous light from the hot platinum strip and to stop down the divergent cathode beam.

(3) The cathode should be as near the fluorescent screen as the sensitiveness of the apparatus permits.

(4) CaO mixed with a small quantity of $BaNO_3$ insures a longer life to the lime and may be easily applied as a paste.

(5) The anode should be near the cathode, for instance, 1 cm. distant.

(6) The potential may be as low as 300 volts and preferably from a constant source, as from storage cells.

(7) The pressure must be very low and may even be assisted with charcoal and liquid air. Gases are given off from

the lime cathode freely and necessitate constant pumping if the tube is to be used for any length of time.

With this hot-lime-cathode apparatus it was easy to observe in the rotating mirror the forms of the current curves when a spark passed and when the current flowed through the corona tube. The field coil was connected in series with the circuit: (1) between the spark gap and the corona tube, and (2) between the corona tube and ground or negative terminal of the generators (see Fig. 52). The current forms are sketched in Fig. 57 as they were observed in both of these positions and for the conditions (N) when there was no spark, (S) when sparks were passing slowly, and (F) when sparks were passing rapidly.

With the coil in the position (1) and with no spark, the current, N_1, was observed to be a unidirectional one with an irregular and ragged edge. These irregularities are noticeable and are probably due to poor commutation at the machines as well as fluctuations in their speed of rotation.

With a few sparks passing, for instance, three per second, the current, S_1, suddenly jumps to a maximum each time a spark passes and then more gradually falls to zero. The current is always in one direction and its maximum value is larger than N_1.

When the spark gap is adjusted so that sparks pass more rapidly, the current, F_1, has the same shape as S_1 except that the impulses are crowded closer together.

With the field coil connected in the position (2), without spark, the current, N_2, is constant and gives a straight line.

With only a few sparks per second a peaked current form, S_2, rises rapidly and decays more slowly than in S_1.

For a greater frequency of sparks the ionization comes into play in a more pronounced fashion. The ionization current does not have time to reduce to zero between consecutive impulses from the spark, and so the resultant effect is a direct current, F_2, ordinarily called a pulsating current, with peaks that correspond to the sparks passing on the other side of the tube.

These current forms are essentially the same both when the wire is positive and negative. They show directly that there are no oscillations in the series spark nor in the corona tube. If there were surges or oscillations left, they would have to be exceedingly weak and

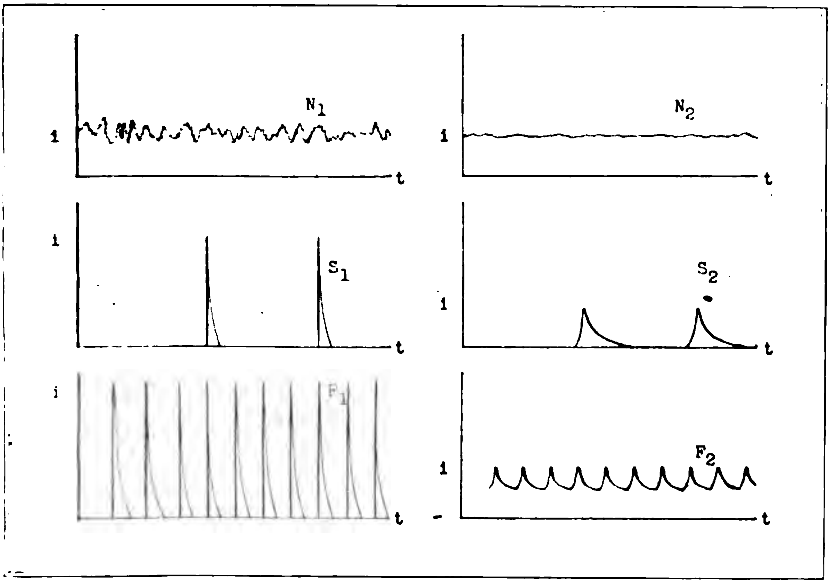


FIG. 57. CURRENT FORMS IN THE SPARK AND CORONA TUBE

of very high frequency. The results of these three methods show conclusively that the corona current with a spark in series is only intermittent and not oscillatory.

32. *The Corona and the Arc.*—Electrical discharges in gases at pressures near that of the atmosphere may be divided into five classes. These are:

(1) The dark discharge, where a small current passes through gas without making itself visible.

(2) The glow discharge, where a larger current passes and the gas in the immediate neighborhood of the electrodes becomes faintly luminous.

(3) The brush discharge, such as that from points where the glow is irregular and extends into the gas some distance from the electrodes.

(4) The spark discharge, which is a transient phenomenon bridging the whole distance between the electrodes, accompanied by a bright light and a comparatively large current.

(5) The arc, in which a large current passes between the electrodes in the gas and the ionized vapors of the electrodes producing a continuous light.

Any one of the first forms of discharge may be converted into any one of the latter forms by an increase in the potential between the electrodes, depending upon the nature and pressure of the gas, and the spacing, size, capacity, and shape of the electrodes.

The corona may be classed as a glow discharge like the positive wire without a spark, or as a brush discharge like the negative beads or the positive streamers. This glow or brush discharge easily goes over into the arc, and in the following paragraphs this transaction will be considered.

It has often been observed that an arc easily forms in the tube when the line switch connecting the tube is opened, especially when the wire in the corona tube is positive and a fairly large current is passing in the discharge. The conclusions drawn from the available data are as follows:

(1) For a given configuration of electrodes the arc-over takes place as soon as the current has reached a certain value which is nearly constant for all pressures.

(2) Arc-over occurs at lower voltages for smaller wires.

(3) At low pressures arc-over for the negative wire occurs at less voltage than for the positive wire.

(4) At high pressures (near atmospheric) arc-over for the positive wire takes place at a less voltage than for the negative wire.

The water resistance connected between the generators and the main bus bar was replaced by a 0.5 ampere fuse in order to see if it had any effect on the corona discharge with and without a spark. The visual forms were studied with the coaxial cylinders (the inner one being No. 20 copper wire) as well as with parallel (No. 20 copper) wires as electrodes.

With the cylindrical electrodes the general results obtained showed that the usual characteristic visual forms of the corona discharge were not materially altered for positive wire or for negative wire with and without a series spark. The only noticeable change was an increased brightness in the positive uniform glow, streamers, and negative beads. With the water resistance cut out the available energy was increased about one hundred times or, in other words, to 10 kilowatts. The negative beads and the positive streamers while much brighter were also in a more agitated state than before the increase in energy. They moved rapidly back and forth on the wire and would go over into the arcing stage much easier than they would with water resistance connected. The axial wire was No. 20 copper tightly stretched, but it was easily set into violent vibrations, at 739 mm. pressure and 12,700 volts, within a few seconds after closing the line switch. The applied potential fluctuated at times as much as 100 volts and the result was a more unsteady discharge. The water resistance has the effect of damping out the smaller variations.

The ease with which the arc formed was also noticed in experiments with No. 20 wires strung parallel with each other, placed ⅛ inch apart and sealed into a glass tube.

With hydrogen it was noticed that when the wire was at a given potential above the critical glow voltage, the current in the beads would increase with the time, the beads would increase in size and in a short time would combine to form an arc. Detailed observations were made on this point.

After the switch was closed, several beads were formed which soon combined into one much larger and brighter, as shown in Fig. 58. This bead seemed to take hold on the wire at a surface irregularity and remained fixed. A bright reddish spot on the wire formed the base of the bead, while a bright blue-white core extended from this spot toward the bright spots on the edge of the observation slot and shaded off into a milky glow or brush. As time proceeded the core grew larger and brighter and the milky glow of the brush reached farther toward the tube, as in *B*. Soon a faint reddish glow, *C*, appeared in the gas, proceeded from the bright spots on the tube, and extended toward the bead. This glow continued to increase in

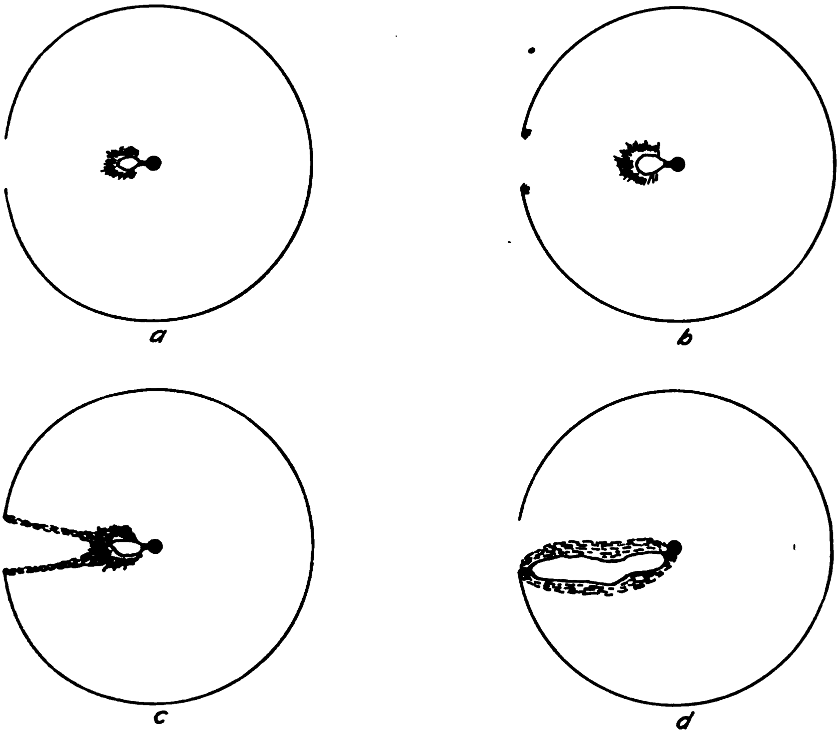


FIG. 58. EVOLUTION OF BEADS INTO THE ARC

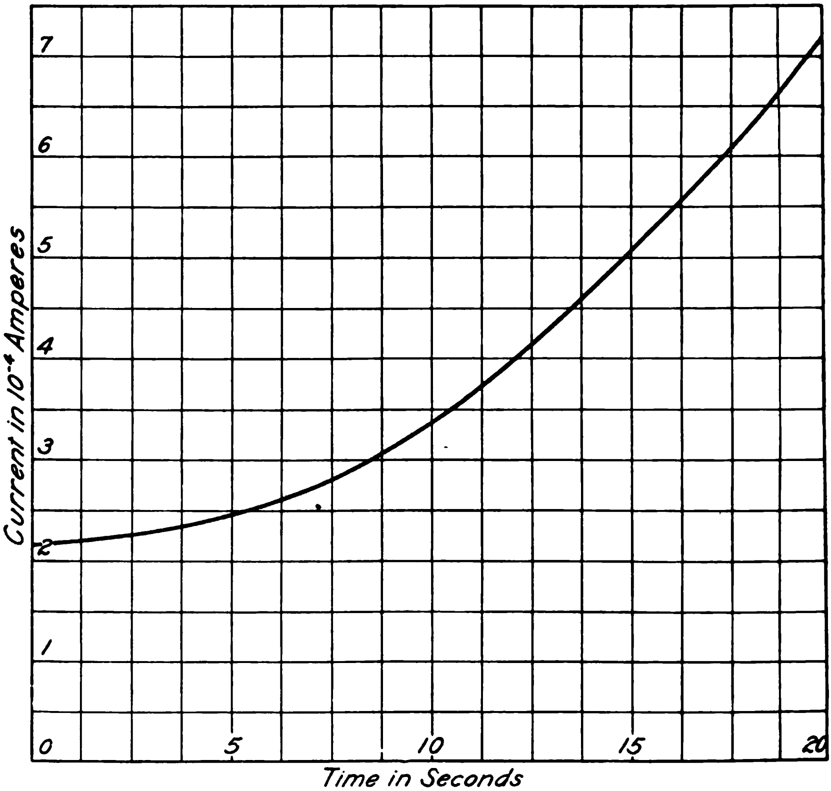


FIG. 59. CURRENT INCREASE WITH TIME FOR POSITIVE STREAMERS

brightness for a short time until the arc, *D*, flashed into existence. The arc had a very bright tubular blue-white core surrounded by a hazy reddish glow and extended from a bright reddish spot on the wire to bright white on the tube. The negative beads and perhaps the positive streamers may be spoken of as miniature or beginning arcs which unite to form a single arc when the current density reaches a certain value.

The curve in Fig. 59 will serve to show how the current in the streamers increases with the time. At a potential of 11,850 volts, somewhat above that for starting corona glow in air at 751 mm. pressure, a spark gap of 0.18 mm. length was placed in series with the tube. Readings of the current were taken at intervals of 5 seconds and when plotted resulted in the given curve. An arc passed shortly after 20 seconds, but the maximum current before it occurred was not obtained.

The increase of the current depends largely on the sparking distance and on the applied voltage (see curve *a*, Fig. 60). When the spark distance from zero is increased, the current for the positive corona decreases accompanied by a decreased brightness of the uniform glow, reaches a minimum value, and as the streamers appear rises to a maximum rapidly and falls off to zero for a large spark distance. The streamers are brightest at the maximum current value and are always connected with a large current. The corresponding negative curves show no such a maximum, with increasing voltage the positive current increases very rapidly.

In order to test the relative magnitude of the current due to the accumulation of ions and that due to the spark, a current-spark dis-

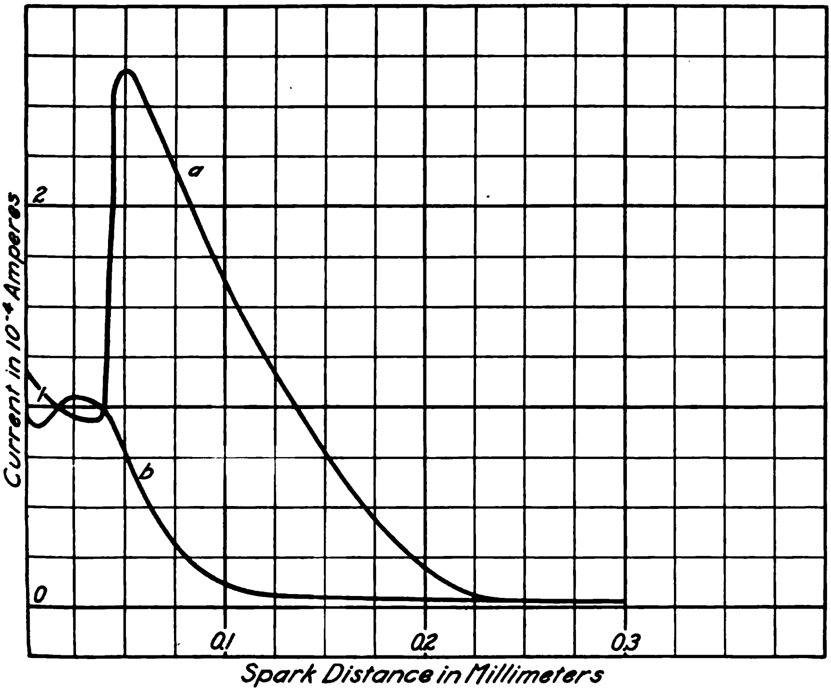


FIG. 60. CURRENT CHANGE FOR VARYING SPARK DISTANCE

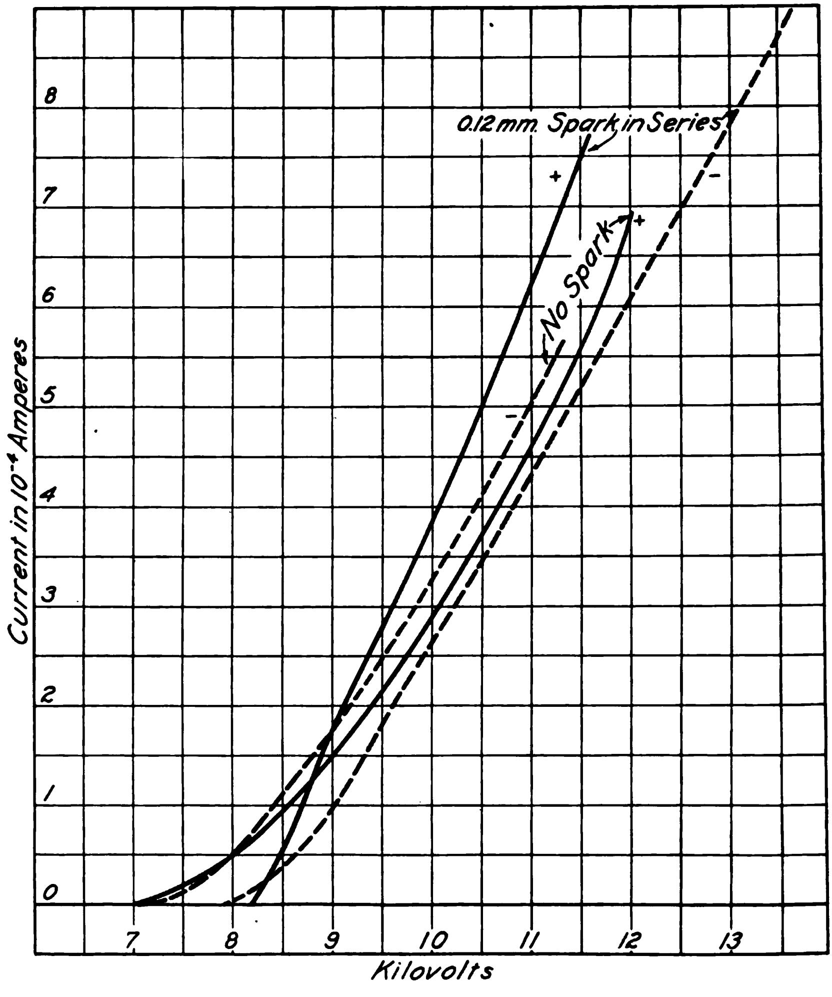


FIG. 61. CHARACTERISTIC CURVES WITH AND WITHOUT SERIES SPARK

tance curve was taken, when the tube was closed, and another when a small current of air was passing through the tube sweeping out some of the ionized gas.

The curves are given in Fig. 60, curve *a*, being taken with the tube closed using a potential of 11,850 volts, and curve *b* with a stream of air passing which necessitated a higher corona voltage; namely, 13,100 volts.

Curve *b* still has the characteristic maximum in the curve, but it is very much reduced in size, whereas curve *a* has a very pronounced maximum of a large value. These curves portray in a striking manner the effect a short spark has in producing a very great ionization in the gas, and also makes it easy to conceive how the positive arc takes place so readily when the switch remains closed for a little time or is suddenly opened while a large current is passing in the tube.

The ordinary characteristic current-voltage curves as obtained in the process of experiments without a series spark give the negative characteristic as lying above the positive. This relative position is maintained in all cases, with one or two minor exceptions.

When a short spark is placed in series with the corona, these positions are reversed and the positive curve lies above the negative, except at the starting point where the curves cross and give a lower starting potential for the negative wire (See Fig. 61). The starting potential with the spark in series is, however, higher than for the other case. It might be pointed out also that the characteristics taken with a series spark are more widely separated than those taken without, and thus they show a wider variation in the current from the positive and negative wires for a given voltage.

It was found when the spark gap was closed while current was flowing that the current would drop in a short time to a position on the ordinary characteristic curve. If the wire is positive at 11,000 volts and a 0.12 mm. spark is in series, for instance, a current of $6.2 \cdot 10^{-4}$ amperes will flow. Short-circuiting the spark gap will cause the current to drop to the value $4.6 \cdot 10^{-4}$ amperes which is a point on the ordinary positive characteristic curve. Similarly by short-circuiting the spark gap when the wire is negative the current will increase to a value which lies on the ordinary negative characteristic. These observations again show that the positive streamers carry a large current.

Without a spark gap in series with the tube, the ordinary uniform positive glow is formed by ionization in the gas near the wire where the field strength is greater than thirty kilovolts per centimeter, the current being carried by both positive and negative ions. The usual negative corona discharge begins critically as a uniform glow similar to that of the positive discharge but has a greater thickness. The brushes or negative beads, soon formed by a slight potential increase, bear a similarity to the arc. This fact, in addition to the position of the negative characteristic curves and to the influence which the surface condition and the material of the wires have on the beads, leads to the belief that an electron emission is present in addition to ionization by collision in the gas.

The case is somewhat different when a series spark gap is used. The corona tube may be considered as a leaky condenser connected in series with a spark gap and a constant source of high potential. A charge will build up to the condenser until the potential difference of the spark gap is sufficient to break down the air between the electrodes. An instantaneous unidirectional current will glow across the spark gap and at the same time the potential across the tube will increase to a point where the corona is formed. The current now passing through the tube will immediately reduce the potential of the spark gap below its critical point and the circuit will be broken. The process is then repeated.

The more nearly uniform appearance of the negative corona can now be explained as a super-imposed building-up and decay of the negative glow discharge through its different stages as the potential on the tube fluctuates. The positive streamers have at times been observed at critical voltages on rough wires when no spark was in series. These streamers are similar to the positive brush discharges observed from pointed electrodes maintained at high positive potentials. Their characteristic presence in the corona tube when a spark is in series is due probably to the sudden impression of a strong field and may be accompanied by a discharge of positive metallic ions, since it has been observed that the surface of the wire becomes disintegrated at points where these streamers are maintained.

The following conclusions have been made:

(1) A spark gap in series with the discharge tube affects the positive and negative corona in very characteristic and striking ways.

(2) The changes are due to intermittent currents.

(3) A hot-lime-cathode Braun tube has been developed and used in observing the weak pulsating currents which pass through the spark and the corona tube.

(4) Evidence has been given to show the relation of the corona to the arc discharge.

(5) An attempt at an explanation of the pulsating current has been made.

CHAPTER XI

Other Types of Corona Discharge

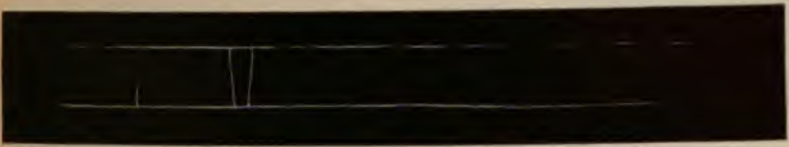
Two wires, 0.167 mm. in diameter, were arranged parallel, two centimeters apart, inside a glass tube. Photographs given in Fig. 62 were taken showing the discharge between parallel wires at reduced pressures with and without a series spark. The three lower half-tones show the typical isolated brush discharge on the negative wire with corresponding luminous sections of the positive wire. The negative brushes had a brilliant nucleus with a fainter glow spreading out from it. For pressures lower than those for which the photographs were taken, the discharge became more brilliant; the brushes spread further apart and increased in size. Each section of the positive glow was usually of uniform brilliancy. For comparatively low pressures and high voltage the positive sections became somewhat discontinuous, and bright spots mixed with the uniform glow.

Two No. 36 wires were stretched three centimeters apart over hard rubber bridges in order to be parallel and the discharge between them was studied. When the visible discharge was fairly started, it took the form of a uniform continuous glow along the negative wire. It was discovered that the humidity of the air had a marked effect upon the discharge.

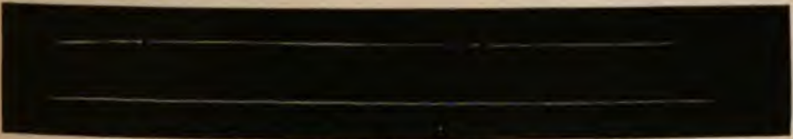
The introduction of a short spark in series made a marked change in the nature of the discharge. Both wires were more or less completely covered with a nearly uniform glow and there was no longer any marked difference between positive and negative (see Fig. 62). At low pressures and relatively high voltage the discharge between the wires resembled a sheet of luminous rain. An intermediate effect had bluish streamers between the wires.

A platinum tip was arranged to be moved from one wire to the other and thus, as shown in Chapter VII, the distribution of potential between the wires was determined. Three explorations were made,—namely, when the voltages were 8,000, 10,000, and 12,000 volts.

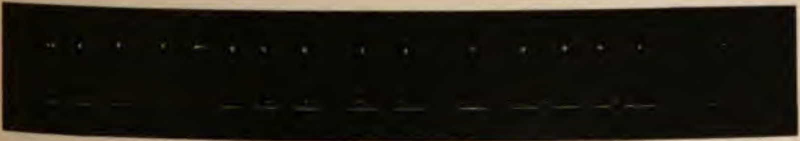
Fig. 63 shows the curves for the field distribution and also the distribution of the field as calculated from the electrostatic formula.



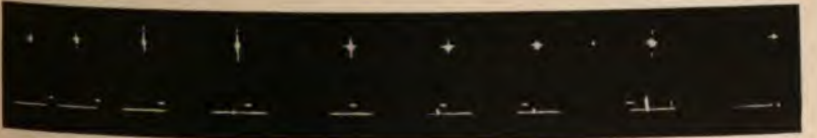
(a) Arc in Series, Pressure 312.2 mm., Volts 8000, Amperes 1.80 × 10^{-4}



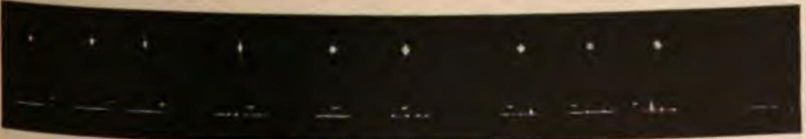
(b) Arc in Series, Pressure 312.2 mm., Volts 8000, Amperes 1.14 × 10^{-4}



(c) No Arc, Pressure 312.2 mm., Volts 8000, Amperes 2.35 × 10^{-4}



(d) No Arc, Pressure 450.0 mm., Volts 8700



(e) No Arc, Pressure 450.0 mm., Volts 8400

Fig. 62. Corona between Parallel Wires at Reduced Pressures
Lower Wire is Positive in Every Case

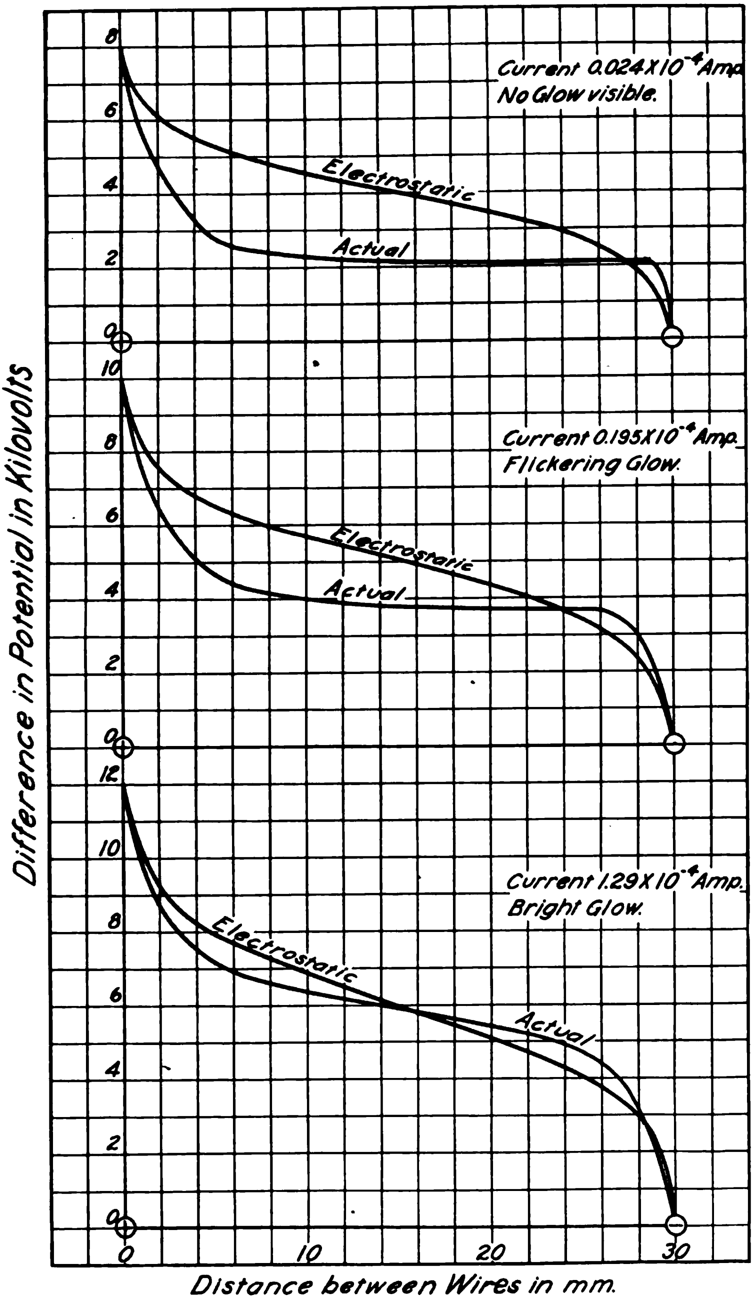


FIG. 63. FIELD DISTRIBUTION BETWEEN TWO PARALLEL 36 B. AND S. GAGE WIRES 3.0 MM. APART

going. The characteristic curves also are similar to those obtained with wire and cylinder.

The experimental knowledge of the corona is still very incomplete. Little has so far been done in the spectroscopic analysis of the various light phenomena which accompany the corona. It has been found, for instance, that the negative beads in hydrogen do not give the characteristic series lines of hydrogen, but rather a continuous band in the red and yellow region of the spectrum. It is hoped the knowledge in this field will be increased in a short time. Mechanical vibrations of the wires and an electric wind have been mentioned occasionally, but these phenomena also require further study.

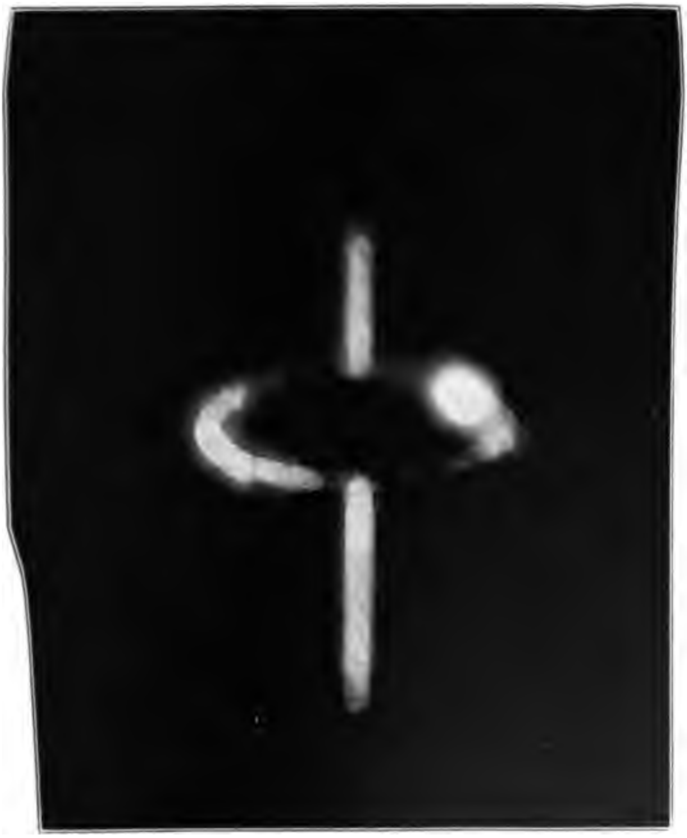


FIG. 64. CORONA ON A WIRE AT THE AXIS OF A SHORT CYLINDER

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THE RELATION BETWEEN THE ELASTIC STRENGTHS OF STEEL IN TENSION, COMPRESSION, AND SHEAR

BY
FRED B SEELY
AND
WILLIAM J. PUTNAM

BULLETIN No. 115

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BULLETIN No. 115 NOVEMBER, 1919

THE RELATION BETWEEN THE ELASTIC STRENGTHS OF STEEL IN TENSION, COMPRESSION, AND SHEAR

BY
FRED B SEELY
ASSOCIATE PROFESSOR OF THEORETICAL AND APPLIED MECHANICS
AND
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ENGINEERING EXPERIMENT STATION
PUBLISHED BY THE UNIVERSITY OF ILLINOIS, URBANA

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THE RELATION BETWEEN THE ELASTIC STRENGTHS OF STEEL IN TENSION, COMPRESSION, AND SHEAR

I. INTRODUCTION

1. *Preliminary.*—This bulletin presents the results of experiments with six grades of steel, three carbon steels and three alloy steels; namely, soft, mild, and medium carbon steel; and vanadium, nickel, and chrome-nickel alloy steel. The elastic strength in tension, in compression, and in shear is given for each of the six grades of steel. The elastic strength in shear is found from tests in torsion with solid cylindrical specimens and with thin-walled hollow cylindrical specimens. Furthermore, a factor is found by the use of which the true or correct shearing elastic strength may be calculated from the elastic strength obtained from a test of a solid specimen. The ratio of this true elastic shearing strength to the elastic tensile strength is given for each grade of steel and its bearing on the theory of combined stress is discussed. The ratio of the elastic tensile strength to the elastic compressive strength is also given and the effect of the amount of rolling upon the elastic tensile and compressive strengths is discussed. The effect of the direction of rolling upon all three elastic strengths is considered for one of the materials; namely, nickel steel.

Our knowledge of the breakdown of elastic action of ductile materials, particularly in the case of combined loading, is far from complete. The various theories of combined stress lead to results which differ rather widely when applied to various machine parts or to structural elements, such as thick cylinders, flat plates, crank shafts, webs of girders, etc. The maximum shear theory of combined stress for ductile materials as expressed by Guest's law, which has gained rather wide acceptance in recent years, assumes that the elastic shearing strength is one-half of the elastic tensile strength. Available experimental results, however, have, in general, failed to justify this assumption. The importance of the limitation imposed by the shearing stress upon the elastic strength of ductile material is, of course, generally recognized. If the maximum strain theory holds until the shearing yield point is reached, as is indicated in recent tests,* it is of special importance to know the relation between the shearing and the tensile (and compressive) elastic strengths for various grades of ductile and semi-ductile steels. The main object of the investigation herein recorded was to determine carefully the elastic shearing strength of ductile and semi-ductile steel and to find the ratio of the elastic shearing strength to the elastic tensile strength with the hope that definite information would thereby be obtained on the breakdown of the elastic action of various grades of steel and on the limits of the theories of combined stress.

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*See Bulletin No. 85, Engineering Experiment Station, University of Illinois, "Strength and Stiffness of Steel under Biaxial Loading," by A. J. Becker.

Apart from the problem of combined stress there has been also a lack of knowledge of the correct elastic shearing strength of various grades of steel and of the general nature of elastic shearing failure as well as of methods of determining the correct shearing strength from tests.

The facts brought out in connection with the elastic compressive strengths of the various materials tested should also add to our knowledge of the elastic behavior of steel and it is felt that questions are raised which may become of considerable importance. There is some evidence indicating that the amount of rolling (roughly indicated by the thickness of the rolled material) may become an important factor in the selection of the proper criterion of elastic strength as well as in estimating the elastic compressive and shearing strengths from a tension test. This question may be of considerable importance in connection with compression members and with certain cases of combined stress. It may also have an important bearing on the problem of the fatigue of steel under repeated stress.

The severe uses under the many and varied new conditions, such as have arisen during the war, and the development of new requirements for machine parts have brought out the need for fuller information on the physical properties of carbon and alloy steel. This bulletin is presented as a contribution toward filling this need.

2. *Acknowledgment.*—All of the experimenting was done in the Laboratory of Applied Mechanics of the University of Illinois. Acknowledgment is made to Professors A. N. TALBOT and H. F. MOORE for the interest shown and helpful suggestions offered during the investigation. Some preliminary experimenting had been done by Professor MOORE to determine the merits of various forms of shear specimens. This work was found to be of considerable value in planning certain parts of the investigation herein described.

II. MATERIALS, TEST SPECIMENS, AND METHOD OF TESTING

3. *Materials.*—As already stated, six grades of steel were tested; namely, soft, mild, and medium carbon steel, and vanadium, nickel, and chrome-nickel alloy steel. Chemical analyses were made of the nickel steel and the chrome-nickel steel only. All of the material except the nickel and the chrome-nickel steel was bought in the open market. The nickel steel specimens were cut from one of the ends of the untested riveted-joint test specimens made for the Board of Engineers of the Quebec Bridge. (The other riveted-joint specimens were tested at the University of Illinois and a report of the tests was made in Bulletin No. 49 of the Engineering Experiment Station.) The chrome-nickel steel specimens were made from ¾-inch square bars of the same material as that used in the chrome-nickel steel riveted-joint specimens also described in Bulletin No. 49 referred to above. The chemical analyses of these two alloy steels as reported in Bulletin No. 49 are given in Table I.

TABLE 1

CHEMICAL COMPOSITION OF NICKEL AND CHROME-NICKEL STEEL

Element	Nickel Steel Per Cent	Chrome-Nickel Steel Per Cent
Carbon	0.258	0.191
Sulphur	0.008	0.035
Phosphorus	0.044	0.042
Manganese	0.700	0.485
Nickel	3.330	0.733
Chromium	.....	0.170

All of the specimens of chrome-nickel steel did not come from the same bar. Three different bars rolled from the same heat were used. The medium steel specimens were made from two bars supposed to be of the same material and billed as 40-point carbon steel. The specimens of each of the other four materials were made from the same bar or piece. All of the material was hot-rolled only. No cold-rolled material was used. The specimens of soft steel came from a bar 3½ inches in diameter by 20 feet in length. The mild steel specimens and also the vanadium steel specimens were cut from a bar ⅞ inch in diameter by 16 feet in length; the nickel steel specimens were cut from a slab 2 inches in thickness by 7½ inches in width. The large soft steel bar (3½ inches in diameter) was used in order to obtain large torsion specimens as well as small ones.

Although the chemical analysis of all of the materials tested cannot be given, the range of material used is well indicated by the elastic tensile strengths as given in Table 2. While some of the material used did not have a well defined yield point, yet all six grades of steel are considered to be ductile or semi-ductile material since the tensile fractured area in all cases showed a considerable reduction.

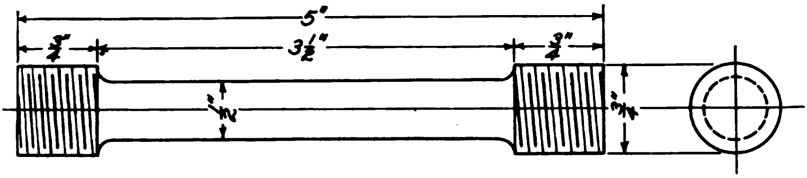
TABLE 2

ELASTIC TENSILE STRENGTHS OF MATERIALS USED

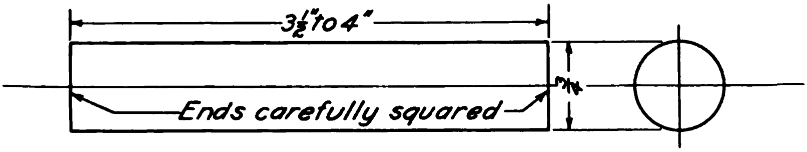
	Materials	Elastic Strength* lb. per sq. in.
Carbon Steel	Soft	21 000
	Mild	32 800
	Medium	45 000
Alloy Steel	Vanadium	52 500
	Nickel	38 000
	Chrome-nickel	35 300

*Proportional limit (see Fig. 5) is here used as a measure of the elastic strength.

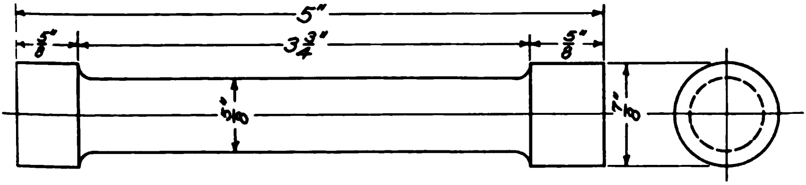
4. *Test Specimens.*—Tension, compression, and shear (torsion) specimens were made from each of the six materials. Both solid and hollow cylinders were used for the torsion specimens; hollow specimens of three different wall thicknesses were tested. In general from three to nine specimens of each type were tested for each material. The total number of specimens tested was 160, exclusive of a considerable number used in preliminary tests in perfecting the measuring apparatus. In obtaining specimens from a bar, care was taken to cut the specimens in rotation so as to avoid the effects of any systematic variation in the properties of the material along the bar. In the case of nickel steel, specimens were cut from a slab 2 inches thick by 7½ inches wide in such a way that the longitudinal axes of some of the specimens were parallel to the direction in which the slab was rolled, while the longitudinal axes of other specimens were perpendicular to the direction of rolling. Large torsion specimens both solid and hollow, as well as small ones, were made from the 3½-inch bar of soft steel.



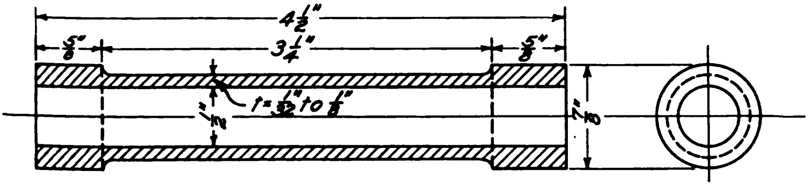
Tension Specimen



Compression Specimen



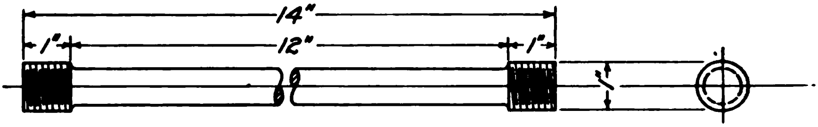
Solid Torsion Specimen



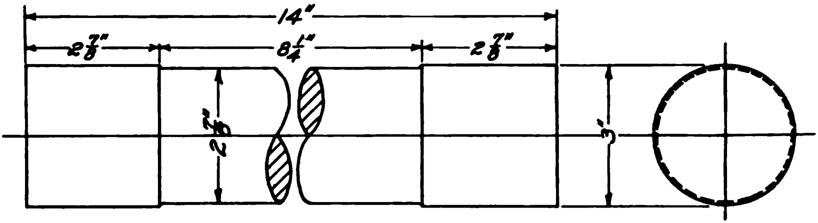
Hollow Torsion Specimen

FIG. 1. FORM AND DIMENSIONS OF SMALL TEST SPECIMENS

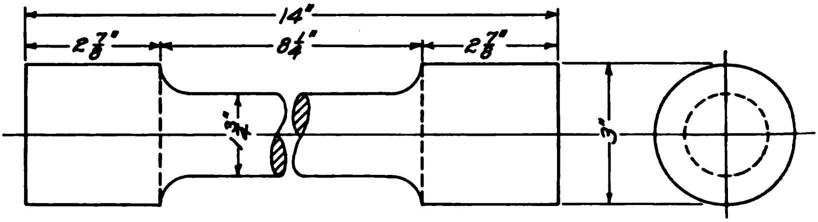
Fig. 1 gives the dimensions of the small specimens used for all the materials and Fig. 2 gives the dimensions of the large specimens of soft steel. Fig 3 shows some of the specimens both before and after testing and also the apparatus used for measuring the thickness of the walls of the small hollow specimens. The length of the small hollow specimens was limited by the length of the ½-inch hole which could be drilled through the specimens from one end. The large hollow specimens were first drilled from both ends and then bored out to the



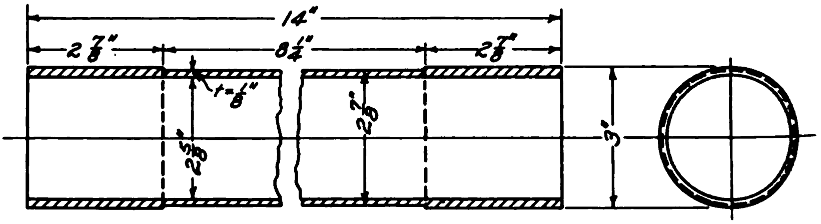
(a), Tension Specimen



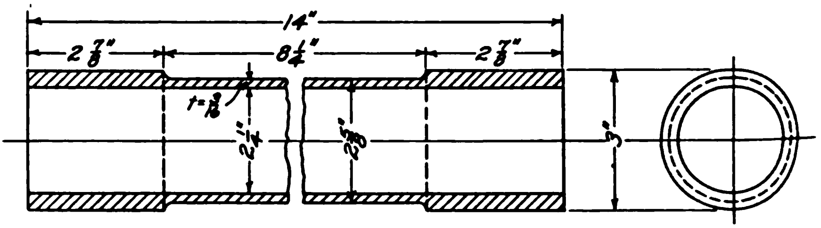
(b), Large Solid Torsion Specimen



(c), Medium Solid Torsion Specimen



(d), Large Hollow Torsion Specimen



(e), Medium Hollow Torsion Specimen

FIG. 2. FORM AND DIMENSIONS OF LARGE TEST SPECIMENS

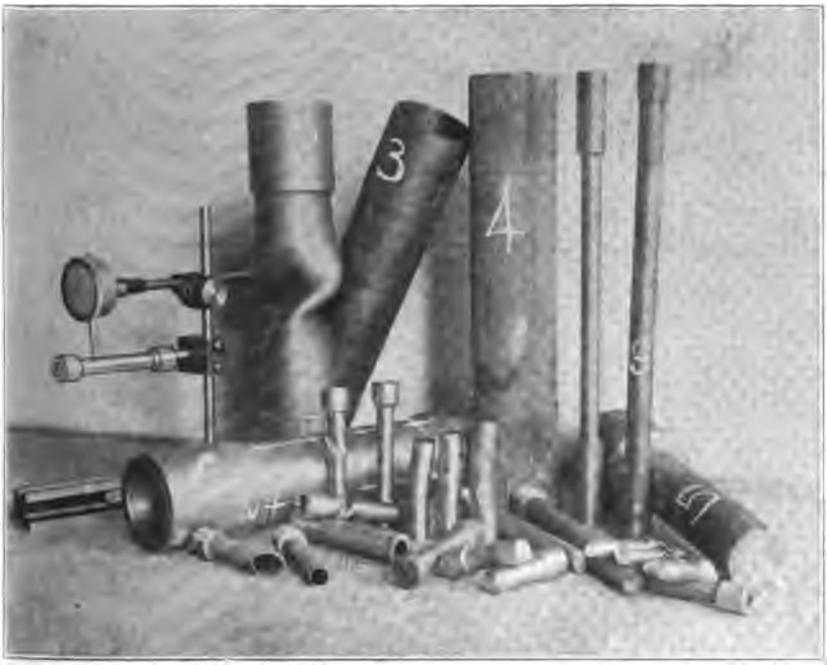


Fig. 3. View of Some of the Specimens

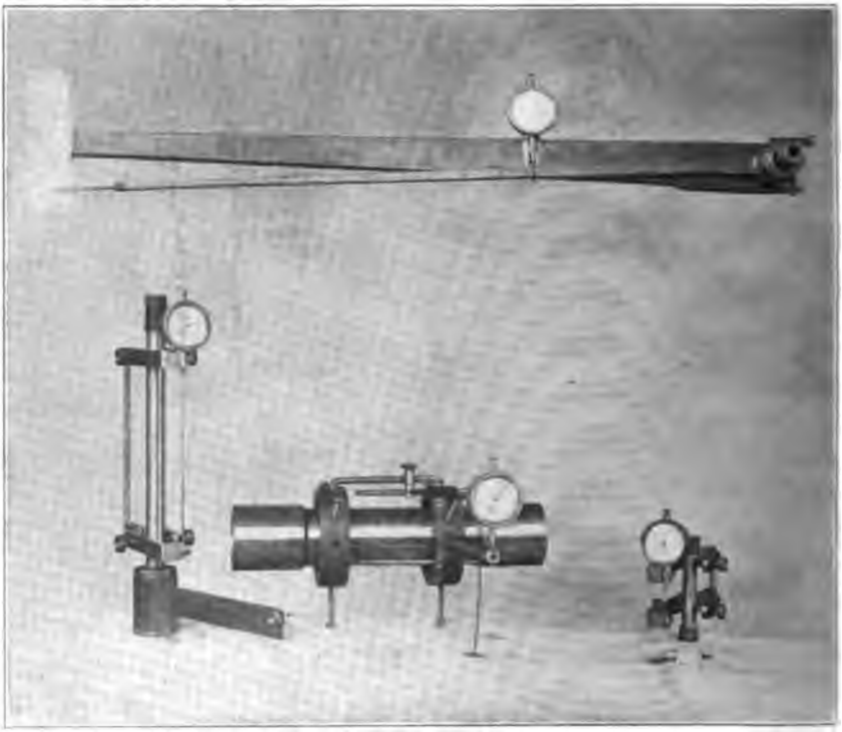


FIG. 4. VIEW OF DEFORMATION MEASURING APPARATUS

desired inner diameter. After the desired inner diameter was obtained, each specimen, whether small or large, was mounted on a mandrel and the outside diameter turned down to the required dimension. The wall thickness of the hollow specimens was measured at four points, 90° apart, around each of four sections along the length of the specimens. The outside diameters at each of the four sections were also taken and the smallest cross section was used in the calculations. The wall thickness could be read to 0.0001 inch. In the case of the large hollow specimens the wall thickness was found in the same way although larger apparatus was required.

5. *Tension Tests.*—The tension test specimens were made with threaded ends and with a diameter of ½ inch (see Figs. 1 and 2). A 2-inch gage length was used with all the specimens except those of soft steel with which a gage length of 8 inches was used. The long specimens of soft steel were used in order to determine the modulus of elasticity more accurately than could be done with specimens having a 2-inch gage length. The modulus of elasticity or stiffness of the various materials, however, is not discussed in this bulletin.

All of the tension tests were made in a 100 000-pound Riehle universal testing machine which had been calibrated over the range used in these experiments. Spherical seated holders were used in all of the experiments.

The extensometers used are shown in Fig. 4. The unit-elongation could be read directly to 0.00025 inch per inch when using a 1/1000-inch Ames dial for a 2-inch gage length, or to 0.000025 inch per inch when using a 1/10 000-inch Ames dial. Both dials were used but it was found that there was little advantage in using the more sensitive dial. The unit-elongation could be estimated to one-tenth of the above values.

6. *Compression Tests.*—The compression test specimens in nearly all cases were made with a diameter of ¾ inch and with a length of 3½ inches to 4 inches as shown in Figs. 1 and 3. A gage length of 2 inches was used in all cases and the deformation measuring apparatus was the same as that used in the tension tests. Care was taken to square off the ends of the specimens in the lathe so that they were smooth and perpendicular to the axis of the specimens. Each specimen was carefully centered in a 100000-lb. Riehle universal testing machine by means of a templet; spherical seated bearing blocks were

used. The testing machine had been calibrated over the range used in these experiments and for a considerable number of tests it was the same machine as was used for the tension tests. The length of specimen used (3½ inches to 4 inches) corresponds to a slenderness ratio value of 19 to 21. In most cases the specimen failed as a flat-ended column (see Fig. 3). It is felt that with the very careful centering the real elastic strength of the material was developed in all cases although the ultimate compressive strength showed considerable variation.

7. *Torsion Tests.*—After some preliminary study and experimenting, a torsion test of a cylindrical specimen was decided upon as being the most satisfactory means for determining the elastic shearing strength of the material. Both solid and hollow cylindrical specimens were used. The small hollow specimen (see Figs. 1 and 3) were made with three different dimensions of the wall thickness for several of the materials; namely, 1/32 inch, 1/16 inch, and 1/8 inch (approximate dimensions), the nominal inside diameter being ½ inch for each specimen. A wall thickness of 1/32 inch makes it possible to determine, very closely, the true elastic shearing strength of the material.

In the case of soft steel, large solid and hollow specimens were made from the 3½-inch bar in addition to the small specimens already described. These large specimens were 14 inches long with a gage length of 5 inches and with a length of 8 inches between shoulders. The diameter, between shoulders, of the first large specimens made was 2⅞ inches for both the solid and the hollow specimens. From the results of the tests, however, it was at first thought that the specimens were not long enough; hence one solid specimen was made 20 inches long and tested, but the results showed no effect due to the changed length. Three solid specimens were then made, 1¾ inches in diameter, for which the load on the machine at the yield point would be about the same as for the hollow specimens. The effect of this change is discussed later. The large hollow specimens were made in two sizes; namely, with a wall thickness of ⅛ inch and an outside diameter of 2⅞ inches and with a wall thickness of 3/16 inch and an outside diameter of 2⅝ inches, as shown in Figs. 2 and 3. In testing the former, plugs had to be fitted into the ends to keep the ends from collapsing in the grips, while in testing the latter this method was not necessary. The ratio of the wall thickness of the hollow specimens to the diameter for the thinner walled specimens is about the same for the large specimens as for the small ones, the value of the ratio being approximately 1 to 20.

All of the large specimens were tested in a 230 000-inch-pound Olsen torsion testing machine, while the small specimens were tested in a Riehle hand power pendulum torsion testing machine. A special light pendulum was used in the Riehle machine for the hollow thin-walled specimens and special apparatus was made for measuring the load. Both torsion machines were calibrated carefully.

All of the small specimens from the 3½-inch bar of soft steel were made by first cutting a 14-inch length of the bar longitudinally into quarters and turning the small specimens from one or more of the quarters.

The apparatus for measuring the deformation in the torsion tests is shown in Fig. 4. Both a 1/1000-inch and a 1/10 000-inch dial were used on each apparatus, so that a considerable range in sensitiveness was obtained to suit the variations in wall thickness, etc.

III. EXPERIMENTAL DATA AND DISCUSSION

8. *Criteria of Elastic Strength.*—Perhaps the best indication of the elastic strength of a material is the elastic limit; that is, the greatest unit-stress which the material can resist without taking a permanent set. The process of determining the elastic limit, however, is so long that it was considered impracticable for the purposes of this investigation.

For the purpose of the comparison of the elastic strengths of various materials or of the same material under different types of stress any one of several unit-stresses as represented on the stress-strain curve may be used. Three such points on the stress-strain curve are used in this investigation; namely, the proportional limit (sometimes called proportional elastic limit), the yield point, and a point between the proportional limit and the yield point called the semi-elastic point or the useful limit point. It is assumed that elastic action only takes place until the proportional limit is reached, while plastic action only occurs at the yield point. Any point on the stress-strain curve between the proportional limit and the yield point corresponds to an action in the material which is partly elastic and partly plastic. Several arbitrary methods have been proposed for conveniently locating such a point. The semi-elastic point or useful limit point used in this investigation is defined as the unit-stress at which the rate of deformation is 100 per cent greater than at zero-stress. This point was used by the Committee of the American Society of Civil Engineers in the analysis* of the tests of large built-up-columns and is very similar to Johnson's apparent elastic limit.† In Fig. 5 the point *U* represents the useful limit point which is found by first laying off *KN* equal to two times *KM* and then drawing a line parallel to *ON* tangent to the stress-strain curve, the point of tangency being *U*. Fig. 5 also shows the proportional limit and yield point.

In the study of the elastic failure of the materials tested, the three criteria of elastic strength mentioned above (porportional limit, useful limit point, and yield point) taken together furnish a safer guide than any one alone. The elastic strengths of the materials tested as

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*Proc. A. S. C. E. Dec., 1917.

†Johnson: The Materials of Construction, p. 10, 1918.

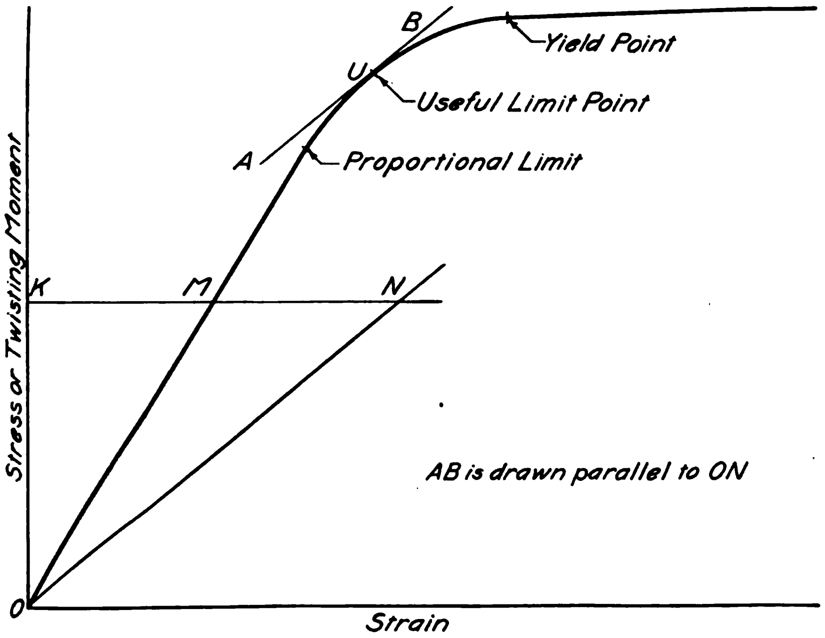


FIG. 5. TYPICAL STRESS-STRAIN DIAGRAM SHOWING THE USEFUL LIMIT POINT

indicated by each of these three criteria for tension, for compression, and for shear are given in Tables 3, 4, and 5 for the individual specimens while the averages are given in Table 6.

9. *Shearing Strengths.*—As has already been stated, the elastic strength in shear was found from tests of solid cylindrical torsion specimens and from thin-walled hollow cylindrical specimens.

It has been commonly recognized that the yield point in shear as found from the test of a solid cylindrical torsion specimen does not represent the correct shearing yield point of the material since all of

TABLE 3

RESULTS OF TENSION TESTS

Gage length 2 in. Diameter ½ in. except as noted. Stress in lb. per sq. in.

Material	Mark	Proportional Limit S_p	Useful Limit Point S_e	Yield Point S_y	Ultimate Strength S_u	Elongation Per Cent	Reduction of Area Per Cent
Soft steel (diameter ¾ in.)	M3-1d	21 000	24 000	29 000	56 100	30.0*	50.6
	M3-T	22 500	27 000	29 000	53 100	50.0	57.6
	M3-2d	20 500	24 000	28 000	56 000	27.0*	53.5
	M3-3d	20 000	25 000	27 500	56 200	29.8*	55.5
	Average	21 000	25 000	28 400	55 400	28.9*	54.3
Mild steel	3	33 000	33 000	33 000	54 900	45.3	68.8
	11	33 000	33 000	35 500	55 500	42.0	70.0
	15	32 000	32 000	32 500	55 000	44.0	69.0
	7	33 000	33 000	33 500	54 300	43.5	63.8
	Average	32 800	32 800	33 600	54 900	43.7	67.9
Medium steel	4-3	46 000	46 000	46 500	77 900	33.5	57.6
	4-7	44 000	44 000	45 000	78 100	33.5	57.6
	Average	45 000	45 000	45 800	78 000	33.5	57.6
Vanadium steel	V-1	53 500	56 000	60 500	109 500	25.0	50.8
	V-3	53 000	54 500	59 000	108 000	23.5	50.8
	V-7	50 000	56 000	59 000	108 000	23.5	52.0
	V-15	53 500	57 000	63 000	110 000	15.6†	34.5†
	Average	52 500	55 900	60 400	109 000	24.0	51.2
Nickel steel Stress parallel to direction of rolling	P-1	35 500	39 000	47 000	87 800	28.5	57.5
	P-2	38 500	40 000	47 000	88 000	28.0	55.2
	Average	37 000	39 500	47 000	87 900	28.3	56.4
Nickel steel Stress perpendicular to direction of rolling	C-1	39 000	40 500	47 000	86 500	17.5	36.0
	C-2	41 000	41 500	48 000	88 100	24.0	51.2
	C2-1d	36 500	40 000	48 000	88 500	22.5	30.0†
	Average	38 800	40 700	47 700	87 700	21.3	39.0
Chrome-nickel steel	L-3	33 500	35 000	38 000	64 500	39.5	62.8
	5-C	30 500	32 500	35 500	67 500	37.5	58.8
	L-5	38 000	38 000	38 500	66 700	38.5	60.5
	8-C	28 000	30 500	36 000	65 500	34.0	64.0
	L8-1d	33 000	35 000	37 500	64 500	37.5	61.2
	L8-2d	36 500	36 500	38 000	65 000	38.0	61.6
	Average	33 300	34 600	37 300	65 600	37.5	61.5

*Gage length 8 in.

†Broke in punch mark.

TABLE 4

RESULTS OF COMPRESSION TESTS

Gage length 2 in. Approximate diameter ¾ in. Length of specimen 3½ in. to 4 in. Stress in lb. per sq. in.

Material	Mark	Proportional Limit S_p	Useful Limit Point S_e	Yield Point S_y	Ultimate Strength S_u
Soft steel	M-C	25 500	25 500	26 200	46 400
	M-10	29 000	29 000	29 000	54 000
	M-S	26 000	26 000	27 200	45 000
	M-11	27 000	27 500	29 000	54 200
	M-T	26 500	26 500	27 000	47 400
	M-12	27 000	27 000	28 500	70 000
	Average	26 800	26 800	27 800	52 800
Mild steel	4	36 000	36 000	37 000	56 000
	8	36 000	36 000	36 500	61 000
	12	32 000	32 500	35 000	54 200
	16	35 000	35 000	35 500	58 700
	Average	34 800	34 900	36 000	57 500
Medium steel	4-4	37 000	40 000	46 000	80 800
	4-8	45 500	45 500	47 000	82 300
	Average	41 300	42 800	46 500	81 600
Vanadium steel	V-4	56 000	57 500	64 000	103 500
	V-8	56 000	58 500	64 000	111 500
	V-12	56 000	58 500	65 000	96 500
	V-1-0	52 500	55 000	64 000	106 000
	V-16	51 000	57 000	63 500	87 000
	Average	54 300	57 300	64 100	101 000
Nickel steel. Stress parallel to direction of rolling	P-3	42 000	46 000	49 000	65 200*
	P-4	42 500	47 000	50 500	99 500
	P-C	36 000	40 000	48 500	79 000
	P-D	37 000	38 000	48 500	86 600
	Average	39 400	42 800	49 100	88 400
Nickel steel Stress perpendicular to direction of rolling	C-A	38 500	43 000	47 500	89 500
	C-B	38 500	41 500	48 000	95 200
	C-4	38 500	40 500	50 000	92 500
	C-5	37 500	40 000	50 000	71 000†
	C-6	40 500	41 500	50 000	61 000†
	Average	38 700	41 300	49 100	92 400
Chrome-nickel steel	L-3	36 500	37 500	41 000	63 400
	L5-1d	39 000	39 000	40 000	70 200
	5-E	37 600	37 600	38 500	......
	L-8	35 500	36 500	39 000	65 700†
	8-H	37 000	37 000	38 500	......
	L5-2d	40 000	40 000	40 500	57 800†
	Average	37 600	37 900	39 600	64 300

*One end crushed. † Both ends crushed.

TABLE 5

RESULTS OF TORSION TESTS

Stress in lb. per sq. in. d = approximate outside diameter in inches
t = approximate wall thickness in inches.
l = gage length in inches.

Material	Type of Specimen	Mark	Proportional Limit S_p	Useful Limit Point S_e	Yield Point S_y	Modulus of Rupture S_r
Soft steel from 3½-in. bar.	Small solid	M-30*	15 400	15 400	17 400	......
		M-3-0	15 400	18 300	19 900	......
	d = ⅝	M-1-D	14 100	14 900	16 800	......
		M-2-D	13 900	15 400	18 500	......
	l = 2	M-3-D	14 600	14 600	15 800	......
		31	14 000	16 500	18 600	60 500
		33	13 600	16 000	18 500	62 500
		34	14 400	17 700	19 000	61 500
		Average	14 400	16 100	18 100	61 500
	Small hollow	MS-1	12 300	13 600	19 200‡	......
		MS-2	11 600	13 400	19 200‡	......
	d = ⅝	MS-3	10 300	12 700	17 000‡	......
	t = 1/32	35	10 700	15 500	21 100‡	30 200¶
		37	11 600	17 000	23 400‡	....
	l = 2	38	13 400	16 900	21 800‡	32 000¶
		Average	11 700	14 900	20 300‡	......
	Large solid	M-1-1	12 300	14 500	20 200	......
		M-4-3	12 900	14 800	20 500	......
	d = 2⅞	M-6-2	13 200	15 500	20 200	......
		M-S-10	14 000	14 400	20 400	......
	l = 5	M-E-0	18 600	19 400	20 800	......
		Average	14 200†	15 700†	20 400	......
	Large hollow	M-2-1	14 300	16 700	18 500	......
	d = 2⅞	M-5-2	14 200	16 100	18 100	......
	t = ⅛	M-7-3	14 300	16 100	17 800	......
	l = 5	Average	14 300	16 300	18 100	......
	Medium solid	MM	17 500	18 500	19 300	59 200
	d = 1¾	MM-0	16 500	18 200	19 100	......
	l = 5	ME-0-1	16 000	17 700	18 900	......
		Average	16 700	18 100	19 100	......
	Medium hollow	MM-1	15 900	16 800	17 800	42 000¶
	d = 2⅜	MM-2	16 000	17 600	18 500	......
	t = 3/16	MM-3	17 600	18 400	19 200	......
	l = 5	Average	16 500	17 600	18 500	......

*Gage length 8 in.

†Results in error as explained in Section 9.

‡Yield point not well defined

¶Collapsed.

TABLE 5—(CONTINUED)

RESULTS OF TORSION TESTS

Stress in lb. per sq. in. d = approximate outside diameter in inches.
t = approximate wall thickness in inches.
l = gage length in inches.

Material	Type of Specimen	Mark	Proportional Limit S_p	Useful Limit Point S_e	Yield Point S_y	Modulus of Rupture S_r
Mild steel from ⅞-in. bar Gage length 2 in.	Solid $d = ⅝$	14	22 700	22 700	23 800	63 400
		2	22 200	22 200	24 200	60 200
		6	24 200	24 200	24 200	......
		10	22 300	22 300	23 300	......
		Average	22 900	22 900	23 900	61 800
	Hollow $d = 0.8$ $t = ⅛$	H	21 000	21 000	21 000	......
		K	21 000	21 000	21 000	......
		L	20 900	20 900	20 900	57 000
		N	21 200	21 200	21 200	57 200
		Average	21 000	21 000	21 000	57 100
	Hollow $d = ⅝$ $t = 1/16$	1	22 600	22 600	23 600	47 600*
		5	20 500	20 500	22 100	......
		9	20 600	20 600	22 900	......
		13	21 600	21 600	23 000	......
		Average	21 300	21 300	22 900	......
	Hollow $d = 0.56$ $t = 1/32$	A	20 000	20 000	21 800	55 000†
		B	20 100	20 100	21 400	33 000*
		C	19 200	19 200	20 500	......
		D	19 800	19 800	20 500	......
		E	19 400	19 400	21 200	......
		Average	19 700	19 700	21 100	......
Medium steel Gage length 2 in.	Solid $d = ⅝$	4-2	30 900	31 600	33 800	79 300
		4-6	31 800	31 800	33 800	......
		Average	31 400	31 700	33 800	......
	Hollow $d = ⅝$	4-1	27 100	27 600	29 300	56 500*
		4-5	26 600	27 400	29 700	69 200†
	$t = 1/16$	Average	26 900	27 500	29 500	......

*Collapsed. †Sheared, rod filled center.

TABLE 5—(CONTINUED)

RESULTS OF TORSION TESTS

Stress in lb. per sq. in. d = approximate outside diameter in inches.
t = approximate wall thickness in inches
l = gage length in inches.

Material	Type of Specimen	Mark	Proportional Limit S_p	Useful Limit Point S_e	Yield Point S_y	Modulus of Rupture S_r
Vanadium steel from 7/8-in. bar Gage length 2 in.	Solid	V-2	32 400	36 000	42 600	......
		V-10	32 200	33 800	43 000	......
	$d = 5/8$	V-6	35 600	37 600	44 000	109 000
		V-14	34 200	37 300	45 000	......
		V-1-V	37 700	39 400	46 500	......
		V-2-V	35 100	39 200	46 500	102 000
		Average	34 500	37 200	44 600	105 800
	Hollow	V-B	37 200	37 200	43 000	......
		V-C	36 200	38 100	42 500	......
	$d = 0.8$	V-20	39 200	39 200	43 000	......
		V-21	37 200	38 000	42 000	......
	$t = 1/8$	V-22	37 700	37 700	42 500	96 000
		Average	37 500	38 000	42 600	......
	Hollow	V-1	36 000	38 000	43 000	......
	$d = 5/8$	V-5	32 800	35 000	43 500	74 300
		V-9	27 800	33 000	41 500	72 800*
	$t = 1/16$	V-13	31 800	34 000	42 000	161 000†
		Average	32 100	35 000	42 500‡	......
	Hollow	V-D	28 300	28 300	44 500	......
		V-E	28 000	28 000	40 500	......
	$d = 0.56$	V-23	26 600	30 400	42 500	72 600†
		V-24	32 000	37 000	50 000	78 000†
	$t = 1/32$	V-25	28 200	31 400	42 700	73 200†
		V-3-V	28 400	34 000	39 800	......
		V-4-V	23 900	29 100	37 400	......
		V-5-V	25 500	29 500	37 600	......
		Average	27 600	30 900	41 900‡	......

*Collapsed. †Sheared, rod filled center. ‡ Yield point not well defined.

TABLE 5—(CONTINUED)

RESULTS OF TORSION TESTS

Stress in lb. per sq. in. d = approximate outside diameter in inches.
t = approximate wall thickness in inches.
l = gage length in inches.

Material	Type of Specimen		Mark	Proportional Limit S_p	Useful Limit Point S_e	Yield Point S_y	Modulus of Rupture S_r
Nickel steel from slab 2 in. thick. Gage length 2 in.	Stress parallel to direction of rolling	Solid $d=\frac{5}{8}$	C-1	22 800	25 800	36 400	72 000
			C-2	25 700	27 400	36 800	......
			C-3	26 000	27 600	......	77 500
			Average	24 800	26 900	36 600	74 800
		Hollow $d=\frac{5}{8}$ $t=\frac{1}{16}$	C-4	27 000	27 000	35 800	64 000†
			C-5	23 500	23 500	34 400	......
			C-6	22 300	26 700	35 300	73 500‡
			Average	24 300	25 700	35 200*	......
		Hollow $d=0.56$ $t=\frac{1}{32}$	C-5d	21 000	23 300	34 200	......
			C-6d	21 500	24 800	34 200	......
			C-1d	23 900	24 400	34 800	......
			C-3d	22 300	24 000	36 200	......
			C-4d	21 000	23 500	35 500	......
			C-2d	22 300	25 700	36 000	......
			Average	22 000	24 300	35 200*	......
	Stress perpendicular to direction of rolling	Solid $d=\frac{5}{8}$	P-4	26 000	28 000	36 500	77 100
			P-5	26 000	30 000	40 500	......
				26 000	29 000	38 500*	......
		Hollow $d=\frac{5}{8}$ $t=\frac{1}{16}$	P-6	24 400	28 200	41 500	75 000‡
			P-7	24 200	27 200	37 000	76 000
			Average	24 300	27 700	39 200*	......
		Hollow $d=0.56$ $t=\frac{1}{32}$	P-8	Spoiled in	testing		
			P-9	20 900	23 700	32 100	......
			P-10	20 600	23 400	31 500	......
			P-11	20 100	23 400	32 200	......
			Average	20 500	23 500	32 000*	......
Chrome-nickel steel. Gage length 2 in.		Solid $d=\frac{5}{8}$	L3-2d	24 100	24 700	26 300	......
			L3-1d	22 800	24 500	27 900	......
			L-5	24 100	25 200	28 000	62 200
			L-8	25 200	26 200	27 200	......
			Average	24 100	25 200	27 400	......
		Hollow $d=\frac{5}{8}$ $t=\frac{1}{16}$	L8	23 800	23 800	24 800	51 200†
			L5	22 300	22 300	23 600	......
			L3	22 300	22 300	24 300	51 600†
			Average	22 800	22 800	24 200	......

*Yield point not well defined.

† Collapsed.

‡Sheared, rod filled center.

TABLE 6

AVERAGES OF THE STRENGTHS OBTAINED FROM THE INDIVIDUAL SPECIMENS IN TENSION, IN COMPRESSION, AND IN SHEAR FOR EACH GRADE OF STEEL TESTED

Stress in lb. per sq. in.

Material	Kind of Stress		Number of Tests	Approximate Outside Diameter Inches	Gage Length Inches	Nominal Wall Thickness Inches	Proportional Limit S_p	Useful Limit Point S_e	Yield Point S_y	Ultimate Strength or Modulus of Rupture S_u or S_v	Elongation Per Cent	Reduction of Area Per Cent
Soft steel from 3½-in. bar	Tension		4	¾	8 and 2	......	21 000	25 000	28 400	55 400	28.9, 50.0	54.3
	Compression		3	¾	2	......	26 800	26 800	27 800	52 800	......	....
	Shear	Solid	8	⅝	2 and 8	......	14 400	16 100	18 100	61 500	......	......
			5	2⅞	5	......	14 200*	15 700	20 400	......	......	......
			3	1¾	5	......	16 700	18 100	19 100	59 200	......	......
		Hollow	6	0.56	2	1/32	11 700	14 900	20 300	......	......	......
			3	2⅞	5	⅛	14 300	16 300	18 100	......	......	......
			3	2⅝	5	3/16	16 500	17 600	18 500	......	......	......
Mild steel from ⅞-in. bar	Tension		4	½	2	......	32 800	32 800	33 600	54 000	43.7	67.9
	Compression		4	¾	2	......	31 800	34 900	36 000	57 500		
	Shear	Solid	4	⅝	2	......	22 900	22 900	23 900	61 800	......	......
		Hollow	4	0.8	2	⅛	21 000	21 000	21 000	57 100	......	......
			4	⅝	2	1/16	21 300	21 300	22 900	......	......	......
			5	0.56	2	1/32	19 700	19 700	21 100	......	......	......
Medium steel from ¾-in. bars	Tension		2	½	2	......	45 000	45 000	45 800	78 000	33.5	57.6
	Compression		2	¾	2	......	41 300	42 800	46 500	81 000	......	......
	Shear	Solid	2	⅝	2	......	31 400	31 700	33 800	79 300	......	......
		Hollow	2	⅝	2	1/16	26 900	27 500	29 500	......	......	......

TABLE 6—(CONTINUED)

AVERAGES OF THE STRENGTHS OBTAINED FROM THE INDIVIDUAL SPECIMENS IN TENSION, IN COMPRESSION, AND IN SHEAR FOR EACH GRADE OF STEEL TESTED

Stress in lb. per sq. in.

Material	Kind of Stress		Number of Tests	Approximate Outside Diameter Inches	Gage Length Inches	Nominal Wall Thickness Inches	Proportional Limit S_p	Useful Limit Point S_e	Yield Point S_y	Ultimate Strength or Modulus of Rupture S_u or S_r	Elongation Per Cent	Reduction of Area Per Cent
Vanadium steel from ⅞-in. bar	Tension		4	½	2	......	52 500	55 900	60 400	109 000	24.0	47.0
	Compression		5	¾	2	......	54 300	57 500	63 100	101 000	......	......
	Shear	Solid	6	⅝	2	......	34 500	37 200	44 600	105 800	......	......
		Hollow	5	0.8	2	⅛	37 500	38 000	42 600	96 000	......	......
			4	⅝	2	1/16	32 100	35 000	42 500	......	......	......
			8	0.56	2	1/32	27 600	30 900	41 900	......	......	......
Nickel steel from slab 2 in. thick Stress parallel to direction* of rolling	Tension		2	½	2	......	37 000	39 500	47 000	87 900	28.3	56.4
	Compression		4	¾	2	......	39 400	42 800	49 100	88 400	......	......
	Shear	Solid	3	⅝	2	......	24 800	26 900	36 600	74 800	......	......
		Hollow	3	⅝	2	1/16	24 300	25 700	35 200	......	......	......
			6	0.56	2	1/32	22 000	24 300	35 200	......	......	......
Nickel steel from slab 2 in. thick Stress perpendicular to direction of rolling	Tension		3	½	2	......	38 800	40 700	47 700	87 700	21.3	39.0
	Compression		5	¾	2	......	38 700	41 300	49 100	92 400	......	......
	Shear	Solid	2	⅝	2	......	26 000	29 000	38 500	77 100	......	......
		Hollow	2	⅝	2	1/16	24 300	27 700	39 200	......	......	......
			4	0.56	2	1/32	20 500	23 500	32 000	......	......	......
Chrome-nickel steel from ¾-in. bars	Tension		6	½	2	......	33 300	34 600	37 300	65 600	37.5	61.5
	Compression		6	¾	2	......	37 600	37 900	39 800	64 300	......	......
	Shear	Solid	4	⅝	2	......	24 100	25 200	30 900	62 200	......	......
		Hollow	3	⅝	2	1/16	22 800	22 800	24 200	......	......	......

*In error, see Section 9 for discussion.

the fibers do not reach their yield points at the same time. The proportional limit, however, as found from the test of a solid cylindrical torsion specimen has, rather generally, been accepted as the correct shearing proportional limit of the material. Obviously, in the test of a solid cylindrical specimen, it is assumed that the first deviation of the stress-strain diagram from a straight line can be detected at the instant the proportional limit of the outermost fiber has been exceeded. With thin-walled, hollow cylindrical torsion specimens the shearing stress is nearly uniform over the section and the proportional limit represents very closely the correct proportional limit of the material. The results of the tests given in Table 5 show clearly that, although the test of a solid cylindrical torsion specimen is very satisfactory for indicating the general quality or character of the material and its reliability for resisting shear, it is not satisfactory for determining the real elastic shearing strength of the material.

TABLE 7

RELATION BETWEEN ELASTIC SHEARING STRENGTHS AS FOUND FROM HOLLOW AND FROM SOLID TORSION SPECIMENS

Material		Ratio $\frac{\text{Shearing Strength, Hollow Specimens}}{\text{Shearing Strength, Solid Specimens}}$		
		Proportional Limit	Useful Limit Point	Yield Point
Soft Steel	Small specimens	.813	.936	1.12*
	Large specimens	.857	.900	.947*
Mild steel		.860	.860	.882
Medium steel		.855†	.868†	.873
Vanadium steel		.800	.830	.940‡
Nickel Steel	Stress parallel to direction of rolling	.886	.904	.962‡
	Stress perpendicular to direction of rolling	.790	.810	.832
Chrome-nickel steel		.946†	.905†	.883

* Yield point of hollow specimens not well defined.

† Probably from 5 to 10 per cent too large because wall thickness of hollow specimens was $\frac{1}{16}$ in. instead of $\frac{1}{32}$ in.

‡ Yield point not well defined for either solid or hollow specimens.

In Table 7 are given values of the ratios of the elastic shearing strength as found from tests of hollow specimens to that found from tests of solid specimens, the elastic strength being indicated by each of the three criteria; namely, proportional limit, useful limit point, and yield point. The results in Tables 6 and 7 justify the following conclusions:

> (a) The shearing proportional limit and also the useful limit point obtained from tests with thin-walled hollow cylindrical torsion specimens is eight-tenths to nine-tenths (0.8 to 0.9) of the proportional limit found from solid cylindrical specimens of the same material and a value of eighty-five hundredths (0.85) may be taken with reasonable accuracy for the ratio of the elastic shearing strength found from thin-walled hollow specimens to the similar strength obtained from solid specimens.
>
> (b) The yield point obtained from hollow thin-walled torsion specimens is eighty-five hundredths to nine-tenths (0.85 to 0.9) of the yield point found from solid cylindrical torsion specimens of the same material. This result applies, of course, only to the materials which have a well defined yield point.

The elastic shearing strength (S_p, S_e, and S_y in Table 5) was calculated in each case from the usual formula, $S = \frac{Tc}{J}$ in which T is the twisting moment (inch pounds), J is the polar moment of inertia (inch^4), and c is the radius of the specimen (inch).

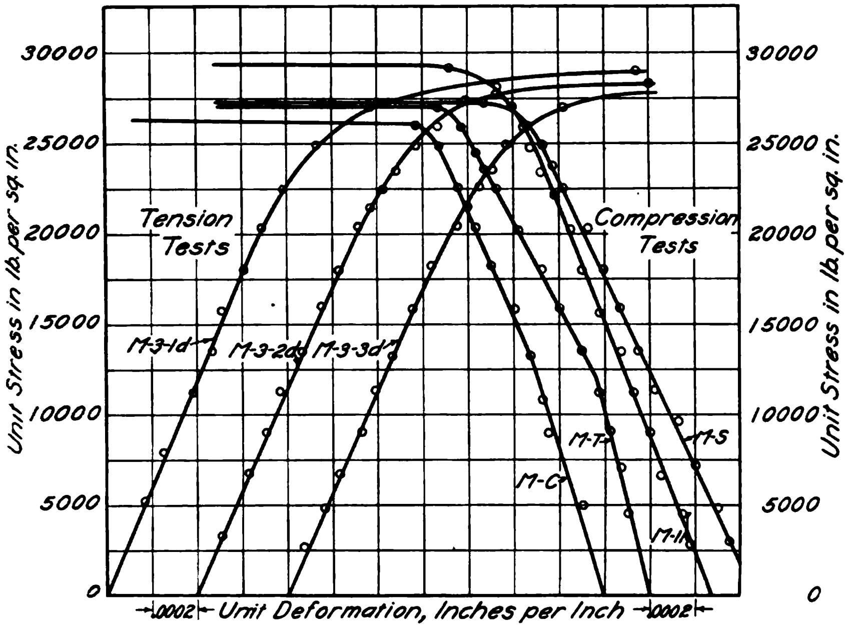
By making use of the conclusions stated above a solid cylindrical torsion specimen may be used with considerable confidence to obtain test results from which the true elastic shearing strength may be calculated for steel likely to be used in general structural or machine construction, although the character or development of the elastic breakdown may be obscured in the test of a solid specimen, as is discussed in the next section. The test results from a solid specimen may also be used, of course, to judge of the general properties, quality, and reliability of the material.

The correct value of the ultimate shearing strength of a material can not be obtained, of course, from a torsion test of a solid specimen, although the modulus of rupture, for many purposes, is a satisfactory indication of the general quality of the material and of the shearing resistance against rupture. It is difficult also to determine the ultimate strength from a thin-walled hollow torsion specimen because the specimen fails by collapsing (see Fig. 3). An attempt was made to prevent collapsing by filling the core of the hollow cylindrical specimen with a close (but not tight) fitting rod. It was found, however, that torque was transmitted to the rod. Two rods were then used, one extending in from each end, with somewhat better results. Although the results given in Table 5 on this point are not sufficient for definite conclusions, they indicate that the true ultimate shearing strength is from eight-tenths to nine-tenths (0.8 to 0.9) of the modulus of rupture as obtained from a test of a solid cylindrical torsion specimen.

It will be noted that in the case of the large torsion specimens of soft steel there seems to be some inconsistency in the results as given in Table 5. For instance, the proportional limit and the useful limit point is less for the large solid specimens than for the hollow specimens; these results are contrary to the above conclusions. It was found that binding occurred at the collar of the roller bearing of the stationary head of the torsion machine, particularly at the relatively large twisting moments required for the large solid specimens. This defect was remedied and the diameter of the remaining solid specimens was reduced to 1¾ inches so as to use about the same load range on the machine as was used with the hollow specimens. The results, therefore, of the tests with the large solid specimens (diameter 2⅞ inches) are not considered further.

The test results of all the small torsion specimens and also of the large specimens of soft steel show that the wall thickness must be thin to obtain the correct elastic shearing strength of the material. The wall thickness of the medium carbon steel and of the chrome-nickel steel specimens was 1/16 inch. From the torsion tests of the other materials in which both 1/16-inch and 1/32-inch wall thickness were used, it appears that the correct shearing strength of the medium steel and the chrome-nickel steel is from 5 to 10 per cent lower than that given in Table 6. The ratios as given in Table 7 for these two materials are, therefore, probably somewhat too large.

10. *Characteristics of Elastic Shear Failure.*—Ductile steel rods or specimens from rolled shapes (any specimens from pieces which have been worked considerably in the forming process) when tested in tension, show a rather sudden or abrupt elastic breakdown culminating in a well defined yield point. Steel which has not been worked much, such as the interior material of large rolled bars, does not show such a sudden failure but gives a more gradual curve for the stress-



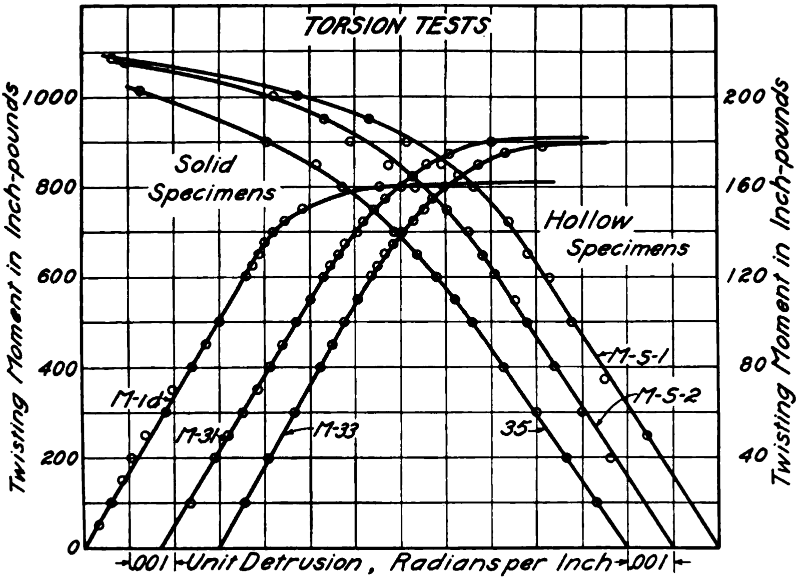


FIG. 6. REPRESENTATIVE STRESS-STRAIN AND MOMENT-STRAIN (TORSION) DIAGRAMS FOR SOFT STEEL—SMALL SPECIMENS

strain diagram (see Figs. 6 and 7 for stress-strain curves for the soft steel from the 3½-inch bar). This point is discussed further in a later section.

The elastic shearing failure of a solid cylindrical specimen of ductile steel when tested in torsion is also rather abrupt with a well defined yield point (see Fig. 8). These facts, backed by the maximum shear theory, by the form of a tensile fracture (cup shaped) and by the slip-lines produced at or near the yield point under repeated load-

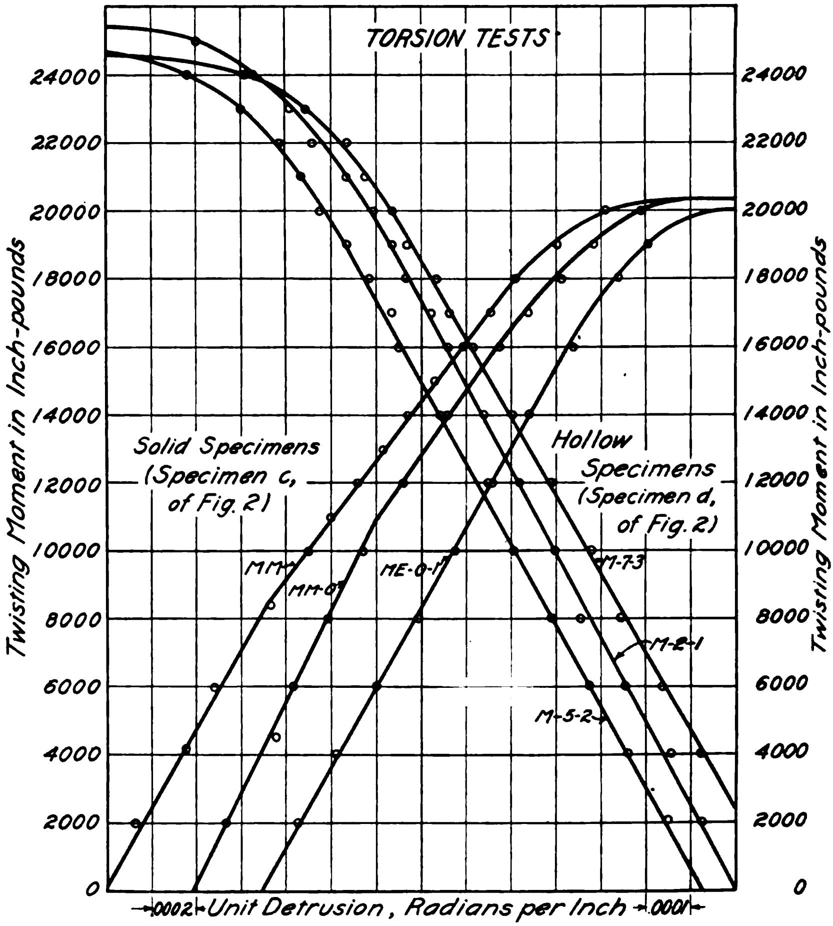


FIG. 7. REPRESENTATIVE MOMENT-STRAIN (TORSION) DIAGRAMS FOR SOFT STEEL—LARGE SPECIMENS

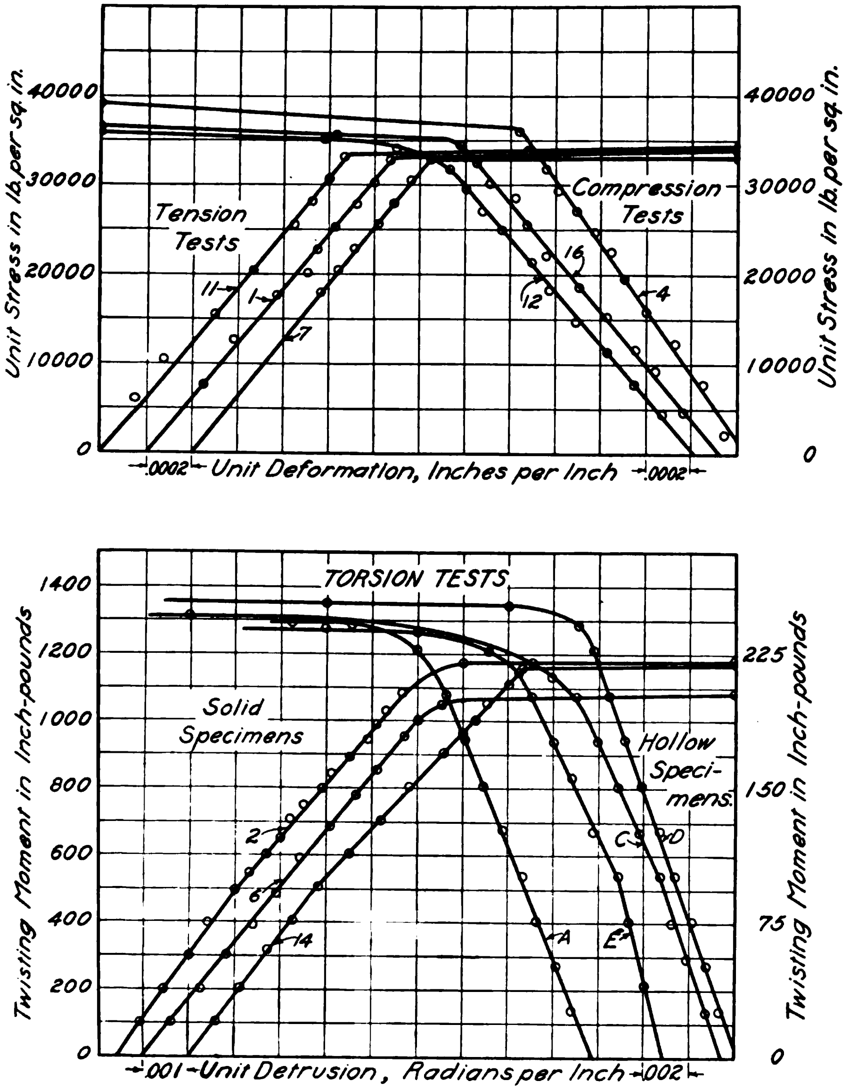


Fig. 8. Representative Stress-Strain and Moment-Strain (Torsion) Diagrams for Mild Steel

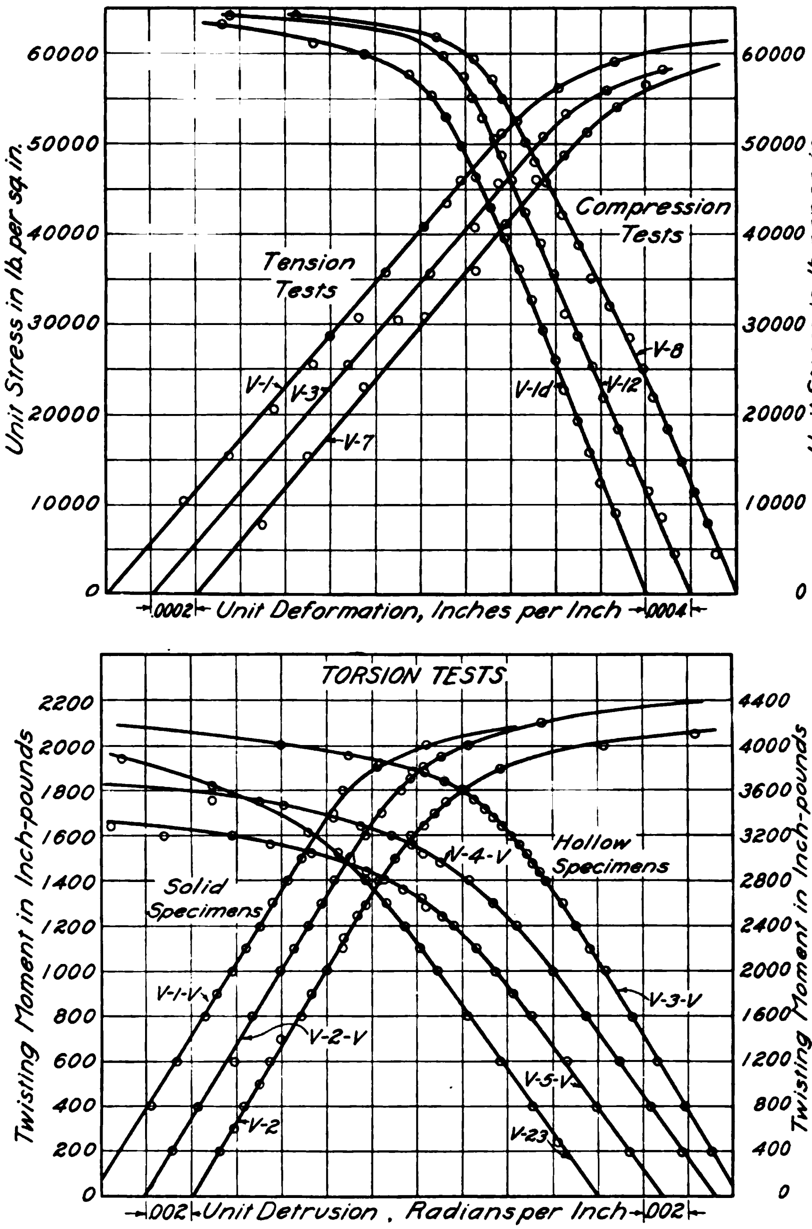


FIG. 9. REPRESENTATIVE STRESS-STRAIN AND MOMENT-STRAIN (TORSION) DIAGRAMS FOR VANADIUM STEEL

ing, have often been used to explain the elastic tensile failure as really a shear failure over an inclined section. And since in a tension test the maximum shearing unit-stress over a section inclined at 45° is one-half of the tensile unit-stress, it has been urged that the elastic shearing strength may best be found from a tension test. Before discussing the experimental data from which the ratios between the elastic shearing and tensile strengths have been found (see next section), it will be well to examine the general character of the elastic shear failure as indicated by the stress-strain diagrams of the thin-walled hollow torsion specimens. From Figs. 6 to 9 which are representative and typical stress-strain diagrams for some of the materials, it will be noted that in most cases the shearing breakdown of elastic action of the various materials is very gradual. In fact, in most cases, it is more gradual than the failure of the elastic action in a tension specimen. It seems difficult, therefore, to account for a tensile elastic breakdown as a failure due to shear, or to have confidence in the use of a tension test for the determination of the elastic shearing strength except for an approximate value. It will also be observed that the solid torsion specimens show a more abrupt elastic failure than a hollow thin-walled specimen of the same material; this fact indicates that the proportional limits of the outer fibers have been somewhat exceeded before a deviation of the stress-strain diagram from a straight line can be detected. This has already been discussed in the section on *Shearing Strength.* The stress-strain diagrams for the medium carbon steel and for the nickel and chrome-nickel steel (not shown) indicate the same characteristics as are shown in Figs. 6 to 9. It appears, therefore, that, contrary to the usual assumption, the shearing breakdown of elastic action of ductile and semi-ductile steel is more gradual than the corresponding tensile or compressive failure.

11. *Ratio of Elastic Shearing Strength to Elastic Tensile Strength.*—Table 8 gives the ratios of the elastic shearing strengths to the elastic tensile strengths for the various materials tested, the elastic strengths being indicated by the proportional limits, the useful limit points, and the yield points. It will be noted from a study of Table 8 that the shearing proportional limits of most of the steels tested are from fifty-five to sixty-five hundredths (0.55 to 0.65) of the tensile proportional limits and that the same statement may be made in the case of the useful limit points. The two materials for which the ratio

TABLE 8

RATIOS OF ELASTIC STRENGTHS IN SHEAR AND TENSION AND ALSO IN TENSION AND COMPRESSION

Material		Ratio Shearing Proportional Limit / Tensile Proportional Limit		Ratio Shearing Useful Limit Point / Tensile Useful Limit Point		Ratio Shearing Yield Point / Tensile Yield Point		Ratio Tensile Elastic Strength / Compressive Elastic Strength		
		Hollow Specimens	Solid Specimens	Hollow Specimens	Solid Specimens	Hollow Specimens	Solid Specimens	Proportional Limit	Useful Limit Point	Yield Point
Soft steel	Small specimens	.558	.685	.596	.645	.715*	.638	.784	.933	1.04
	Large specimens	.680	.795	.652	.724	.638	.672			
Mild steel		.600	.698	.600	.698	.628	.682	.943	.940	.932
Medium steel		.597†	.698	.611†	.705	.644	.738	1.09‡ or .989	1.05‡ or 1.01	.965
Vanadium steel		.526	.657	.553	.637	.694*	.739	.950	.972	.943
Nickel steel	Stress parallel to direction of rolling	.594	.670	.615	.681	.749	.780	.939	.923	.956
	Stress perpendicular to direction of rolling	.520	.670	.577	.710	.671	.807	1.00	.985	.972
Chrome-nickel steel		.642†	.683	.650	.698	.637	.814	.886	.887	.942

*Yield point of hollow specimens not well defined.

†Probably 5 to 10 per cent too large since hollow specimens with $\frac{1}{16}$ in. wall thickness were used instead of $\frac{1}{32}$ in.

‡Probably in error: only two specimens tested in compression one of which gave very low results (see Table 4).

varies most from the average are the soft steel (large specimens) and the vanadium steel. Owing to the fact that the tension specimens of soft steel were made by quartering a 14-inch length of the 3½-inch bar, they contained much of the inner or "heart" material of the large bar, while the large hollow specimens contained none of the "heart" material. It is doubtful, therefore, whether the tension specimens should be considered as of the same material as the large hollow specimens. Greater variation also was noted in the test results with the soft steel specimens than with the other materials (see section 13 for further discussion). In connection with the vanadium steel it should be stated that due to the greater hardness of the vanadium steel, it was more difficult to produce a smooth hole in drilling out the center of the hollow specimens of this material than of the softer materials. The wall thickness as measured, therefore, may be slightly too large, because the grooves or tool marks were, perhaps, not properly taken into account. If this statement is true, the values of the ratio for vanadium steel are somewhat too small. This statement may also explain the somewhat greater variation in the values of elastic strengths obtained from the thin-walled (1/32 inch thick) vanadium specimens than in those obtained from the corresponding specimens of most of the other materials. It may also account for the greater difference between the results obtained with 1/32-inch and 1/16-inch wall thicknesses for vanadium steel than for the other steels. It is possible, however, that the ratio for vanadium steel is somewhat lower than for the other steels tested.

With these facts in mind it is felt that a study of Table 8 justifies the conclusion that the elastic shearing strength of steel likely to be used in general construction of machines or structures is close to six-tenths (0.6)* of the elastic tensile strength, instead of one-half (0.5) of the elastic tensile strength as assumed in the maximum shear theory of combined stress as expressed by Guest's law. In other words, ductile or semi-ductile steel will not suffer elastic breakdown when the shearing unit-stress developed is one-half of the elastic tensile strength of the material; hence the field in which the maximum strain theory may hold is not as limited as would be the case if the elastic shearing strength were one-half of the tensile strength. The influence of this fact upon the design of machines or structures under combined loading such as thick cylinders, flat plates, crank shafts, girders, etc., can

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*The value of six-tenths is also found by Becker with biaxial loading, see Bulletin No. 85, p. 43, Engineering Experiment Station, University of Illinois.

TABLE 9

RESULTS OF EARLIER EXPERIMENTS

Experiments by Platt and Hayward*

Materials	Tensile Yield Point† lb. per sq. in.	Ratio $\frac{\text{Torsion, Yield Point}}{\text{Tension, Yield Point}}$
Wrought iron (N. Crown)	33 700	.598
Wrought iron (S. C. Crown)	38 400	.597
Rivet iron	37 700	.615
Siemens Martin steel	37 700	.604
Bessemer steel	69 800	.647
Crucible steel	69 600	.623
Rivet steel	40 000	.571
Cast steel	38 600	.604

Experiments by L. B. Turner‡

Materials	Tensile Proportional Limit	Ratio $\frac{\text{Torsion, Proportional Limit}}{\text{Tension, Proportional Limit}}$
Mild steel¶ (0.15% C)	31 600	.519
Mild steel§ (0.32% C)	42 300	.577
Tool steel§ (1.25% C)	67 700	.568
Nickel steel§ (3.01% Ni.)	81 200	.503

Experiments by E. L. Hancock**

Materials	Tensile Proportional Limit	Ratio $\frac{\text{Torsion, Proportional Limit}}{\text{Tension, Proportional Limit}}$
Steel tubing	21 000	.500
Nickel steel	76 500	.497
Mild carbon steel	47 000	.649
Steel (Scoble)	64 600	.451
Carbon steel	35 500	.688
Rivet steel	38 900	.602
Nickel steel	56 000	.643
Steel tubing	17 000	.677
Steel tubing	28 000	.576
Steel tubing	20 000	.600

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*Proc. Institution of Civil Engineers, Vol. 90, p. 382, 1888.

†Yield point found by drop of beam.

‡Engineering (London), February 12, 1909, and July 28, 1911.

¶Specimens made of thin-walled tubing.

§Specimens made of small solid rods, [illegible] in. (tension) and 0.33 in. (torsion).

**Proc. A. S. T. M., p. 370, 1908.

not be discussed here. It makes possible more efficient and economical use of material, under certain conditions, than would be the case if the shearing strength were one-half of the tensile strength.

12. *Results of Earlier Experiments.*—Results of tests of various grades of steel in simple tension and simple torsion made by Platt and Hayward, by L. B. Turner, and by E. L. Hancock are given in Table 9. Platt and Hayward used solid bars 1½ inches in diameter for both tension and torsion tests. The yield point as found by the drop of the beam was used as the elastic strength for both tension and torsion. Two specimens in tension and three in torsion were used for each material. Initial strains were first taken out by repeated loadings. Considering the method of determining the elastic strength and the fact that the elastic strength was of secondary importance in the investigation, the results for the ratios of the elastic strengths in torsion and in tension as found by Platt and Hayward (Table 9) agree well with the values of the same ratio as herein recorded (Table 8).

In the tests by Turner the specimens of mild steel with 0.15 per cent C. were made from annealed weldless steel tubes with an outside diameter of 1 inch and wall thickness of 0.022 inch (No. 24 B.W.G.) for both tension and torsion tests. The wall thickness was not measured for each specimen but an average thickness was determined for twelve short (1 inch) portions cut from three tubes taken at random. The mean thickness was found by first weighing the portions in air and then in water. There was considerable variation in thickness from point to point around a section of a cut portion; in some cases an eccentricity was perceptible to the naked eye. Considerable variation in thickness was shown among the results of the individual specimens. Twenty-one specimens of this particular material were tested.

The specimens for the other three materials tested by Turner were solid ⅜-inch rods for the tension tests and ⅜-inch rods turned down to 0.33-inch diameter for a length of 3½ inches for the torsion tests. The number of specimens was much less than for the steel tubing. All of the specimens were annealed. Nickel steel specimens showed the greatest variation in the results of the individual specimens.

The yielding of all the specimens was very sudden. In all cases the proportional limit and the yield point coincided. This result is quite contrary to the results found in the tests which have already been explained in this bulletin.

When the method of determining the wall thickness of the hollow specimens, the small size of the solid torsion specimens, and the difference in the method of experimenting are considered, the ratios of the elastic strengths in torsion and in tension as found by Turner (Table 9) are in fair agreement with the values of the same ratio as found from the tests herein described (Table 8).

The results of the tests by Hancock show considerable variation. No description of the material is given other than its name in Table 9 and nothing is stated as to the kind or number of specimens used or the method of testing except that the proportional limit was used as a measure of the elastic strength. The results indicate a fair agreement with the results herein recorded for most of the materials, although the low values for the ratio of shear (torsion) to tension for some of the materials is not found by any of the other experimenters.

The values for the ratio of the elastic strengths in tension and in shear as indicated in tests with combined loading have not varied much from 0.6. Becker* found values of 0.59 and 0.62 for two grades of steel tubing. Scoble's† tests are the only ones which indicate that the ratio is less than 0.5 and his criterion of elastic strength and method of experimenting seem somewhat unusual.

A study of the earlier experiments discussed above bear out, in the main, the conclusions already stated for the results presented in this bulletin; namely, that the elastic shearing strength of ductile and semiductile steel varies but little from six-tenths (0.6) of the elastic tensile strength.

13. *Ratio of Elastic Tensile Strength to Elastic Compressive Strength.*—The elastic strength in tension and in compression for ductile steels is usually considered to be the same. This assumption is sufficiently accurate for many purposes. In the problems of combined stress and in built-up compression members, however, it is important to know accurately the relation between the elastic tensile and compressive strengths and particularly to know how the strengths are affected by mechanical treatment of the steel such as the amount of working during the rolling process. Tables 6 and 8 indicate that the elastic compressive strength of ductile steel is somewhat greater than the elastic tensile strength except in the case of soft steel. It is clear from a study of Table 8 that the amount of working or rolling has a

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*Bulletin No. 85, Engineering Experiment Station, University of Illinois.

†Philosophical Magazine, May, 1906.

marked effect upon the elastic tensile and compressive strengths of steel. Table 8 indicates that steel which has been rolled into comparatively thin plates or small shapes has an elastic compressive strength approximately 5 per cent greater than the elastic tensile strength whether the elastic strength is judged from the proportional limit, useful limit point, or yield point. In the case of soft steel from the 3½-inch bar which represents material with relatively little working in the rolling process, the compressive proportional limit is much greater (27 per cent) than the tensile proportional limit, while the yield point in compression is somewhat less (4 per cent) than the yield point in tension (see Fig. 6 and Table 8). It appears, therefore, that the criterion of elastic strength may be of much importance, that the tension test so generally used to judge of the elastic properties of steel is not wholly reliable, and that it may be necessary to resort to auxiliary compression tests for material to be used under certain conditions of combined stress and for critical compression members,* at least, until test results and the treatment received by the material can be correlated through more extensive experimental investigations. To what extent the increased compressive strength due to rolling may be attributed to compacting, causing a denser material, or attributed to the arrangement of the crystals of the constituent elements in steel or to other factors is not definitely known. The problem offers opportunity for fruitful experimental work. It was noted that the breakdown of elastic action in compression is fully as gradual as that of the corresponding tensile failure (in most cases more so) except in the case of soft steel. This fact suggests that compacting of steel may be an important factor in determining its strength. The maximum shear theory (Guest's law) of the breakdown of elastic action assumes that the elastic tensile and compressive strengths are the same. The results of Table 8 give further evidence that Guest's law is not an accurate interpretation of the elastic failure of all ductile steel.

14. *Effect of Direction of Rolling.*—It is generally recognized that the direction of rolling of hot-rolled steel influences the grain or

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*In the tests of large built-up columns conducted by Bureau of Standards for the Committee on Steel Columns and Struts of the American Society of Civil Engineers, (see Proc. A. S. C. E. Dec., 1917) it was found that the columns built up of ⅛-inch to ⅞-inch material showed a considerably lower strength in most cases than those of ⅜-inch material. Compressive tests on specimens sawed from the thick portions showed a decrease in the compressive yield point of 6000 pounds per square inch as compared with the tensile yield point of the same material, while the compressive yield point of specimens sawed from the thin portions was nearly the same as the tensile yield point.

crystal growth or formation, by making the grains or crystals longer in the direction of rolling. It is usually assumed, however, that the elastic strength of the material is not affected by the direction of rolling or, in other words, that the elastic strength is the same in all directions. Some experimental results were obtained on this point in the case of nickel steel. As already stated the specimens of nickel steel were cut from a rolled slab 2 inches thick by 7½ inches wide. From this slab some specimens were cut with their longitudinal axes parallel to the direction of rolling and others with their axes perpendicular to the direction of rolling. Specimens whose axes are parallel to the direction of rolling, when tested in torsion, develop shearing stress perpendicular to the direction of rolling and when tested in tension and compression, of course, develop stress parallel to the direction of rolling, while the reverse is true for the specimens whose axes are perpendicular to the direction of rolling.

The results given in Tables 3, 4, 5, and 6 for nickel steel, although not entirely consistent, fail to indicate any systematic influence of the direction of rolling on the elastic strength of the material either for tension, compression, or shear. However, the ductility as measured by the ultimate tensile elongation and reduction of area shows a marked effect of the direction of rolling. The effect on the ductility is also very noticeable in the appearance of the fracture. While the values given in Table 8 for nickel steel seem to indicate some effect of direction of rolling, a study of the more detailed data in Tables 3 to 6, reveals little if any effect on the elastic strength. The ultimate strengths in tension, in compression, and in shear also show no influence of the direction of rolling. Whether much thinner material such as used for boiler plates, rolled sections, etc., would show more effect of the direction of rolling is not known.

15. *Summary.*—The severe uses to which carbon and alloy steels are put in some phases of engineering, as for example, in automobile and in aeroplane construction, have developed a need for more detailed knowledge of the action of steel, both within and beyond the elastic limit, under various types of stress, as well as of the factors which affect the physical properties of the material. This need, in time, may require some modifications in the tests of the materials and in the methods of interpreting the tests. The following brief summary of the chief points brought out by this investigation are offered as a con-

tribution toward filling part of this need. The conclusions apply to hot-rolled carbon and alloy steels which are representative of those likely to be used in general structural and machine construction.

(1) The correct value of the elastic shearing strength of steel as measured by the proportional limit or the useful limit point may be determined from a torsion test of a hollow thin-walled cylindrical specimen. The correct value of the yield point in shear is also shown in the test of a hollow thin-walled torsion specimen.

(2) The correct value of the elastic shearing strength of steel as measured by the proportional limit or the useful limit point may be taken, with reasonable accuracy, as eighty-five hundredths (0.85) of the elastic strength obtained from a torsion test of a solid cylindrical specimen. The correct value of the yield point for the more ductile materials is slightly more than eighty-five hundredths (0.85) of the yield point obtained from a test of a solid torsion specimen.

(3) A solid cylindrical torsion specimen, therefore, may be used to obtain test results from which the correct value of the elastic shearing strength and the shearing yield point of steel may be calculated by the use of a correction factor, although the character or progress of the breakdown of the elastic action may be obscured in the test of the solid specimen. Test results obtained from a solid specimen may also be used, of course, to judge of the general properties, quality, and reliability of the material.

(4) The correct value of the elastic shearing strength of steel as measured by the proportional limit or the useful limit point is from fifty-five to sixty-five hundredths (0.55 to 0.65) of the elastic tensile strength and may be taken with reasonable accuracy as six-tenths (0.6) of the elastic tensile strength. The maximum shear theory of the failure of elastic action of ductile steel (sometimes called Guest's law) is, therefore, not an accurate statement of the law of elastic breakdown, since Guest's law assumes that the elastic shearing strength is one-half (0.5) of the elastic tensile strength. The maximum shear theory as expressed by Guest's law, however, is of much use in obtaining approximate results.

(5) Contrary to the general belief, the breakdown of the shearing elastic action of ductile and semi-ductile steel as found in these tests is gradual; more gradual, as a rule, than the failure of elastic action in a tension specimen.

(6) The amount of hot-rolling received by steel may have a marked effect upon the relation of the elastic tensile and compressive strengths. For the material from ¾-inch and ⅞-inch bars, the elastic compressive strength is somewhat greater (about 5 per cent) than the elastic tensile strength whether the elastic strength is measured by the proportional limit, useful limit point, or the yield point. For the material from the 3½-inch bar, the compressive proportional limit is very much greater (27 per cent) than the tensile proportional limit, while the compressive yield point is somewhat less (4 per cent) than the tensile yield point.

(7) It appears, therefore, that the choice of the criterion of elastic strength may be of considerable importance in some cases, and that the usual tensile test of material may require supplementary compressive tests or a better correlation between test data and the amount of treatment received during rolling, before the elastic properties of the material as obtained from tensile test data can be relied upon.

(8) The elastic strength and ultimate strength of steel in tension, in compression, and in shear is affected little, if any, by the direction of rolling in the case of a slab 2 inches thick, although the ductility, as measured in tension tests by the percentage of elongation and percentage of reduction of area, is materially less when the stress is perpendicular to the direction of rolling than it is when the stress is parallel to the direction of rolling.

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BITUMINOUS COAL STORAGE PRACTICE

BY
H. H. STOEK
C. W. HIPPARD
W. D. LANGTRY

BULLETIN No. 116

ENGINEERING EXPERIMENT STATION

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URBANA, ILLINOIS.

UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

BULLETIN No. 116 JANUARY, 1920

BITUMINOUS COAL STORAGE PRACTICE

BY

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ENGINEERING EXPERIMENT STATION
PUBLISHED BY THE UNIVERSITY OF ILLINOIS, URBANA

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THE STORAGE OF BITUMINOUS COAL

I. INTRODUCTION

1. *Interest in Storage of Coal.*—One result of the coal shortage during the winter of 1917-1918 was to impress upon the general public, and particularly upon the Fuel Administration, the necessity of having a coal pile on which to draw in time of stress such as occurred during the winter of 1918.

Upon the recommendation of the Illinois Fuel Administration, a systematic campaign was instituted by the United States Fuel Administration in Washington, urging people to store coal. The conclusions and recommendations of the Engineering Experiment Station Circular No. 6* were reprinted in condensed form and given wide publicity by several State Fuel Administrations, by the Retail Coal Dealers Association of Illinois and Wisconsin, and by the National Board of Fire Underwriters. As a result of this campaign, it is safe to say that never before had so much attention been paid to the storage of coal as was the case in the spring and summer of 1918.

During the past year unusual attention has also been given to the subject of coal storage in England and in Canada and the conclusions which were reached in these countries, and which will be referred to later in fuller detail, agree very closely with the experience in the United States.

Details as to the amounts of coal in storage at different periods and the methods used to stimulate storage will be found in the reports of the Fuel Administration.

2. *Conditions under which Coal Was Stored.*—The present bulletin aims to supplement Circular No. 6 by presenting information secured in a further study of the shortage of coal under conditions somewhat different from those that existed prior to the publication of Circular No. 6 in the early part of 1918. These new conditions were:

(1) On account of the pooling of coals from a number of different districts and the zoning system of distribution

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* "The Storage of Bituminous Coal," by H. H. Stock. Univ. of Ill., Eng. Exp. Sta. Circular No. 6, 1918.

under the United States Fuel Administration during 1918, many were compelled to buy a different coal from that to which they had been accustomed in the past.

(2) It was often impossible to secure continuous shipments of the same coal; therefore it was frequently necessary to store a mixture of coals.

(3) Owing to the great demand for a maximum output under war conditions, less care was given to the preparation of the coal, with regard both to its sizing and to the separation of impurities; consequently much coal was stored that was not suitable for the purpose.

(4) Owing to the campaign for storing coal carried on mainly by government agencies, undoubtedly much more coal was stored than under ordinary conditions, and much of this was stored by people without any previous experience in the storing of coal.

In some cases, therefore, the results of storage during 1918 were discouraging to those who had no previous experience in storing coal. One purpose of this further study of the subject was to find out the experience of those who stored under these unusual conditions and, if necessary, to modify the conclusions and suggestions contained in Circular No. 6.

3. *Sources of Information.*—The data for the present bulletin were obtained:

(1) From a questionnaire sent to the same individuals or companies upon whose experience the conclusions published in Circular No. 6 were based. These included about two hundred individuals, manufacturing concerns, railroads, coke plants, etc., that had stored coal under widely differing conditions.

(2) From a similar questionnaire which, through the cordial coöperation of **JOSEPH HARRINGTON**, Administrative Engineer of the Illinois Fuel Administration, was sent to about eighteen thousand power plants in Illinois. From this questionnaire about three hundred answers were received.

(3) From a careful study of fires in coal piles in Chicago. This study was made by W. D. **LANGTRY** in con-

nection with work begun under the Conservation Department of the United States Fuel Administration in Illinois. J. C. McDONALD, chief of the Bureau of Fire Prevention and Public Safety of Chicago, for a period of six months beginning about May 1, 1918, reported daily all fires in coal piles in Chicago and either MR. LANGTRY or MR. HIPPARD, Research Assistant in Mining Engineering of the Engineering Experiment Station, investigated most of these fires and, in many cases, took photographs of them.

(4) From investigations made by the authors of this bulletin of fires which occurred in Mattoon, Decatur, Rock Island, Moline, Davenport, Aurora, Champaign, Urbana, St. Louis, and Milwaukee. The fires in these cities had been reported either to the local fire departments or to the County Fuel Administrators who were most helpful by notifying the authors of coal in storage and of fires. The conditions under which fires occurred in these cities were similar to those under which fires occurred in Chicago.

(5) From information furnished through the cordial coöperation of E. A. McAULIFFE and the following supervisors of the Fuel Conservation Section of the United States Railroad Administration: E. P. ROESCH, ROBERT COLLETT, B. R. FEENY, H. C. WOODBRIDGE, N. CLEWER, J. W. HARDY, and L. R. PYLE.* S. W. PARR, Professor of Industrial Chemistry, University of Illinois, whose bulletins on spontaneous combustion are well known, has been most helpful through suggestions and criticisms of the manuscripts. MR. HIPPARD not only coöperated with MR. LANGTRY in studying Chicago fires, but also compiled the data secured in connection with these fires and the replies to the several questionnaires. So many have coöperated in gathering information that it is impossible to give adequate credit to all by name.

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* See "Storage of Coal by Railroads during 1918," by H. H. Stock. Inter. Ry. Fuel Assoc. Proc., 1919.

II. SUMMARY OF CONCLUSIONS

It is believed that the following conclusions will be helpful to any one who expects to store coal. These conclusions and the evidence upon which they are based are discussed in detail in the subsequent pages of this bulletin.

4. *Preliminary Considerations.*—

(1.) Storage of coal insures the consumer a regular supply of coal, assists in equalizing freight traffic on the railroads, and helps to stabilize the operation of coal mines.

(2) The storage of coal should not be undertaken without a careful consideration of the practice of those who have stored coal successfully.

(3) Before it is time to begin the actual storing a suitable place should be prepared and a policy outlined far enough in advance so that every one who will have to do with the storing can receive definite instructions and not mere suggestions. It is unwise to wait until the coal to be stored is on the track and then to dump it anywhere so as to release the cars promptly. When storing begins, the instructions should be carried out to the letter. Many failures in storing coal have been due, not to faulty instructions, but to the fact that the instructions have not been followed.

5. *Preparation of Place of Storage.*—If possible a place should be chosen that is dry and well drained; if not drained naturally, drains should be provided about the storage pile, not underneath it, as a drain beneath a pile may produce an air current up through the pile and thus assist spontaneous combustion.

Coal should not be dumped on ground covered with ashes or refuse of any kind, because often in addition to furnishing flues for the admission of air, such refuse contains combustible material: furthermore, the presence of such refuse will depreciate the value of the coal when it is reclaimed from storage. If possible, the ground should be cleared of vegetation and leveled off, so that the reclaiming of the coal will be made as easy as possible and that, in reclaiming, dirt and refuse will not be taken up by the shovel or by other devices used. There is some justification for the objection of firemen to using coal that has been stored, because of the dirt and other refuse that has been mixed with the coal in taking it from the storage pile. A hard clay bottom thoroughly drained is desirable, if a concrete is too expensive.

If possible, adequate space should be provided so that the coal can be moved, if heating occurs. Coal should not be piled around hot pipes, against a boiler, against hot walls, around a chimney, or in any place where it will be subjected to outside heat, because the liability to spontaneous combustion increases rapidly with a rise in temperature. Coal should not be stored above flues that will permit a current of air to enter the coal pile; hot air such as that from a sewer is particularly to be avoided.

6. *Time of Year for Storage.*—In order best to equalize transportation facilities, to help stabilize mine operation, and sometimes to take advantage of lower prices, coal should be stored between the first of May and the first of September. However, as these are the hottest months of the year, special precautions should be taken both in storing and in watching the coal after it is placed in storage. Coal is a poor conductor of heat and if coal that is already at a high temperature is covered by other coal, it retains the heat and is much more liable to spontaneous combustion than coal that is stored at a lower temperature.

7. *Kinds of Coal which May Be Safely Stored.*—It is probably true that all varieties of bituminous coal have been stored without fire resulting, and equally true that all varieties of coal have fired when stored. These facts do not mean that all coals store equally well, as there is undoubtedly a difference in coals in this respect. The kind of coal that is to be stored should be specified. Coals that are known to be particularly liable to spontaneous combustion should not be selected for storage if it is possible to avoid doing so. If there is no choice of coal to be had, greater precautions in piling and in watching storage piles will be necessary.

The spontaneous combustion of coal is due largely to the oxidation of fine coal; consequently, the liability to spontaneous combustion in stored coal is greatly reduced and in many cases eliminated if dust and fine coal can be kept out of the pile.

Hence, if possible, cleaned, screened coal of a uniform size should be chosen, the larger the lumps the better, so as to give the greater number of voids in the pile. Coal of one size is better than a mixture of sizes.

Sized coal should not be stored upon a foundation of fine coal.

The coal should be handled in such a way as to prevent breakage as much as possible. If there is a choice of coals for storage, the least friable should be chosen and the one in which there is the least fine material.

While many varieties of mine-run coal cannot be stored safely under ordinary conditions because of the presence of fine coal and dust, such coal has been successfully stored in small, low piles. In storing mine-run coal, it should be piled uniformly so as to prevent segregation of the sizes.

As fine coal or slack is more liable to spontaneous combustion than clean sized coal, it should be very carefully watched in storage to detect evidence of heating.

8. *Sulphur in Coal.*—Although experimentation has shown that the sulphur contained in coal in the form of pyrites is not the chief cause of spontaneous combustion as was formerly supposed, yet the oxidation of the sulphur in the coal not only produces heat but also assists in breaking up the lumps and thus increasing the amount of fine coal in the pile. Any considerable rise in temperature from either external or internal sources promotes the oxidation of the iron pyrites. This oxidation produces heat and thus increases the liability of the coal to spontaneous combustion. It is wise to select low sulphur coals for storage if obtainable, but it must not be taken for granted that a low sulphur coal will necessarily store well.

9. *Method of Piling.*—

(1) Coal should be so piled for storage that any part of the pile can be moved promptly if necessary.

(2) Coal should be so piled that air may circulate freely through it and thus carry off any heat generated, or else so closely packed that air cannot enter the pile; i.e., under

water storage conditions should be approximated as nearly as possible.

(3) Stratification or segregation of fine and lump coal should be avoided, since an open stratum of coarse lumps provides passage for air to reach the fine coal but not in sufficient quantity to keep down the temperature of the pile. Coal should be spread in horizontal layers and not dumped in conical piles, for in the latter case the fine coal stays in the center at the top of the pile and the lumps roll to the bottom.

(4) The depth and area of storage piles will be determined largely by the storage space available and the mechanical appliances to be used. Other conditions being equal, the deeper the pile and the greater its area the greater the difficulty in inspecting it, and in moving it quickly if necessary. Hence, a number of small piles, if practicable, are better than one large pile. Lack of space, however, usually prevents such spreading out of the coal. It is impossible to specify exact heights as so much depends upon the kind of coal and upon local conditions.[*]

(5) The hazard of spontaneous combustion seems to be independent of whether the coal is piled in the open or under cover.

10. *Moisture.*— The exact effect of moisture in connection with spontaneous combustion is not known, and, as shown in later pages, the evidence of laboratory experiments is contradictory.

The repeated wetting and drying of coal seems to increase the tendency to spontaneous combustion. This may be due to the breaking up of the coal which such alternate wetting and drying occasions, even if there is no chemical reaction between the water and the coal. It is not wise to put wet coal into a pile, or to store coal on a damp base if it can be avoided. After a rain or snowstorm a coal pile should be carefully inspected and watched.

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[*] The Railroad Administration has suggested piling coal for railroad storage not over twelve to fifteen feet in height when the track is placed on top of the coal pile, and not over twenty feet when a locomotive crane is used.

The Home Insurance Company advises against piling in excess of twelve feet, or more than one thousand five hundred tons in any pile, and suggests trimming the piles so that no point in the interior is more than ten feet from an air cooled surface. These are wise precautions, but frequently impossible of application on account of lack of storage space.

Water is an effective agent in quenching fire in a coal pile only if it can be applied in sufficient quantities to extinguish the fire and to cool the mass. The water must be applied at the source of the fire, for it can do little good if the stream is only played on the surface. To be sure that the water reaches the fire it is usually necessary to turn over the coal.

It is advisable to have water and hose available for use in case of necessity, but water should be used carefully and only as a last resort after other means, such as moving the coal, have been tried to lower the temperature. An effort should be made to determine the seat of the heating and to remove the coal affected, which should be spread out on the ground and allowed to cool off in the air, if possible. Only in case of necessity should water be used to cool it. If coal is ablaze it is necessary to add water, which very often will so control the fire that the danger to surrounding buildings is reduced, and more time is allowed to move the coal. Coal that has once heated should preferably be used at once and not be returned to the pile.

11. *Inspection and Precautions.*—There should be an inspector at each storage pile who not only is competent to inspect the coal furnished but who also has authority to reject it if not according to specifications and to see that the storage instructions are carried out.

Coal in storage should be inspected regularly and if the temperature reaches 140 degrees, the pile should be very carefully watched. If the temperature continues to rise rapidly and reaches 150 to 160 degrees, the coal should be moved as promptly as possible and the coal thus moved should be thoroughly cooled before being replaced in storage, or still better, it should be used at once. If the temperature rises slowly the pile should be carefully watched, but it is not necessary to begin moving the coal at as low a temperature as when the rise is rapid, for the temperature may recede and the danger be past.

Coal should be moved before it actually smokes. Such smoking is reported to begin at 180 degrees Fahr., though there is no very definite information on this point. Steaming should not be confused with smoking, for steam is frequently seen coming from a pile and this does not necessarily indicate a danger point. Temperature tests of coal in storage should be made, if possible, and one should not depend on such indications of fire as odor or smoke coming from the coal.

for when the coal reaches this stage it is well along in the process of combustion. Every storage plan should give special attention to loading out the coal quickly and promptly, if necessary.

Inflammable material, such as waste, paper, rags, wood, rosin, oil, and tar in a coal pile often form the starting point for a fire, and every effort should be made to keep such material from the coal as it is being placed in storage. Irregular admission of air into the coal pile around the legs of a trestle, through a porous bottom such as coarse cinders, or through cracks between boards, etc., should be avoided.

It is very important that coal in storage should not be subject to such external sources of heat as steam pipes, because the susceptibility of coal to spontaneous combustion increases rapidly as the temperature rises.

The effect of ventilating of coal piles is a disputed point, but the weight of evidence in the United States seems to be against the practice. This may possibly be due to the fact that ventilation has been inadequately done. The imperfect ventilation generally attempted in the United States is certainly disadvantageous, though reports from Canadian practice favor ventilation.

About 75 per cent of the coal pile fires studied have occurred within ninety days after the coal was placed in storage; hence particular attention should be given to the pile during the first three months that it is in storage. The greater the area of the pile exposed to the air the more quickly will the danger be passed.

Coal stored during the summer should, if possible, not be drawn on in the early fall, as is so often done, but kept for the time of congestion in railroad traffic, which usually occurs from December to March.

Finally, safety in the storage of coal depends upon careful attention to the details given in the foregoing conclusions, which represent the experience of a large number of those who have stored coal in amounts varying from a few tons up to hundreds of thousands of tons, and under widely different conditions.

A storage plan must consider all of the conditions, and not only a part; for instance, clean, lump coal of a certain kind may be stored with perfect safety in high piles; while the same coal, run-of-mine or unscreened, may not be safely stored at all, or at least only in small piles. Lack of attention to details in storage or failure systematically to inspect storage piles and to be ready for any emergency that may occur, may result in losses from fires.

For such amounts as are required by the ordinary householder, namely, ten to twenty tons a year, it can be positively stated (a) that there is little or no danger of spontaneous combustion if the foregoing suggestions are followed and (b) that there is no appreciable deterioration in the heating value.

As the amount of coal stored increases, increased care must be taken in the method of storing and in watching the coal after storage.

III. EXPERIENCE IN THE STORAGE OF COAL DURING 1918-1919

DATA SECURED BY QUESTIONNAIRES

12. *Introduction.*—As was previously mentioned, an effort has been made by means of questionnaires to secure information that would confirm, modify, or refute the conclusions upon the storage of coal as given in Circular No. 6.

Questionnaire *A* (see Appendix I) was sent to those from whom the information was obtained that was used in the preparation of Circular No. 6. This list included about one hundred and seventy-five individuals and companies who stored coal under widely different conditions and in greatly differing amounts, varying from the ordinary householder storing from ten to twenty tons, to such industries as the by-product coke companies, wholesale distributors of coal, large utilities companies, railroads, etc., storing as high as hundreds of thousands of tons. An effort was also made to include all varieties of storage; i. e., at the mines, by railroads, by large and small power plants, etc.

Questionnaire *B* (see Appendix I) was sent to the power plants of the State through the courtesy of Joseph Harrington, Administrative Engineer, United States Fuel Administration, Chicago.

It is realized that data obtained by questionnaires are somewhat uncertain, because of the difficulty of having those who fill out the questionnaires understand fully just what is desired in answer to the questions, and also because the data furnished may be interpreted in a sense different from that intended by the one filling out the questionnaire. However, it is probable that these difficulties are more than balanced by the much larger amount of material that can be gathered by the questionnaire method; by averaging a large number of answers these inaccuracies are minimized. As far as possible any ambiguity in the answers was cleared up by additional correspondence.

The data for the fires in Chicago were secured in person by either Mr. Langtry or Mr. Hippard who had unusual opportunity for obtaining first-hand information concerning these fires.

In tabulating and studying these data many variables must be considered, which are so interrelated that great care must be taken to avoid drawing erroneous conclusions from any one set of figures by failing to consider them in their proper relation to the other factors, even when these related factors cannot be expressed in the tabulated material. Therefore, general conclusions should not be drawn from isolated statements and tables.

13. *Kinds of Coal that Can Be Stored.*—Table 1, giving a statement of fires by districts from which the coal was obtained, not only substantiates the conclusions published in Circular No. 6 that

TABLE NO. 1

GEOGRAPHICAL SOURCES OF SUPPLY OF STORED COAL

DISTRICT	Questionnaire *A*						Questionnaire *B*					
	Fired		Not Fired		Total		Fired		Not Fired		Total	
	Not Mixed	Mixed	Not Mixed	Mixed	Not Mixed	Mixed	Not Mixed	Mixed	Not Mixed	Mixed	Not Mixed	Mixed
Arkansas		1				1						
Cape Breton	1				1							
Colorado		1	1		1	1						
Eastern Pool	1				1							
Illinois:												
Christian-Macon Co.							12	2	30	1	42	3
Danville	1				1		1		1		2	
Franklin Co.	4	4	8	2	12	6	15	5	88	4	103	9
Longwall		1				1	5		21		26	
Peoria	2				2		7	1	9		16	1
Saline	1		1		2		2	1	7	1	9	2
Springfield	4	3			4	3	11	2	26	1	37	3
Standard	1	1	3		4	1	7	1	10	1	17	2
District not known	2	2			2	2	3		19		22	
Illinois and Indiana							1		2		3	
Indiana:												
Clinton			3		3		1				1	
Mercer Co.							1		1		2	
Northern				1		1						
Pike							1				1	
Terre Haute								1	1	2	1	3
No. 4 Vein	1		2		3							
District not known		2				2	1				1	
Iowa		1				1						
Kentucky	2	2		2	2	4			2	2	2	2
Lake Ports Pool	3				3							
Michigan, Bay Co.	1				1							
Ohio	1	1	1	1	2	2			1		1	
Oklahoma		1	1		1	1						
Pennsylvania												
Anthracite			1		1							
Bituminous	4		4		8			1				1
Red Lodge (Montana) sub-bit.			1		1							
Virginia									1		1	
West Virginia	2	3	2	4	4	7			3	1	3	1
Totals	31	23	28	10	59	33	68	14	222	13	290	27

"most varieties of bituminous coal may be safely stored if of proper size and free from fine coal and dust," but also suggests the even more general conclusions: *that although practically every kind of bituminous coal has been stored without spontaneous combustion occurring, yet under certain conditions spontaneous combustion has occurred with practically every kind of coal stored.*

Table 1 also shows that the percentage of fires in piles of mixed coals is considerably greater than in piles of the same coals unmixed. Although no satisfactory explanation of the phenomenon has been offered, the opinion is very generally held that a mixture of two coals is more liable to spontaneous combustion than either one separately, and all the evidence gathered seems to support this opinion.

The Commonwealth Edison Company of Chicago, which has been very successful in storing large amounts of coal, reports that between February 26 and April 14, 1918, it stored at the Fisk Street plant about 3000 tons of central Illinois coal, principally egg and lump from one particular mine and a small amount of coal of the same size from two other mines, one located in central and the other in southern Illinois, together with six cars of run-of-mine coal from the same mines. The ground was cleared of old coal before the new coal was stored. During the early part of August, 1919, the pile was found to be heating and a part was removed and used at once.

Another phase of the question concerns the placing of fresh coal upon coal that has been in storage for some time, and a number of fires have been cited as taking place at the junction of the fresh and the old coal soon after the fresh coal had been placed in storage. For several fires investigated by the writers there was no other apparent cause. No explanation of this has been offered, and it is a subject requiring further investigation.

14. *Sizes of Coal that Can Be Stored.*—Tables 2 and 3 show that the fire hazard for piles of clean, sized coal is relatively small, compared with that for piles of screenings or mine-run, and that the size is an important factor in connection with storage. Table 2 shows that 56 per cent of all the piles of mine-run fired, and that 85 per cent of the piles of screenings fired. Table 3 shows that 88 per cent of the fires occurred in mine-run or screenings. Of the 98 storage piles of mine-run about 23 per cent fired, while of the 86 storage piles of screenings, 51 per cent fired. Of the 132 storage piles of sized coal less than 7 per cent fired.

These results appear conclusive enough to support the recommendation that screenings or mine-run should not be stored in large quantities excepting under water, but if it is necessary to store these sizes in any other way, they should be very carefully watched for evidences of heating and means provided for rapidly and promptly moving the coal if heating is detected. A mixture of sizes gives a pile much less void space and hence the heated air is less readily carried off.

TABLE 2
EFFECT ON SPONTANEOUS COMBUSTION OF SIZE OF COAL
QUESTIONNAIRE A

SIZE OF COAL	Fired			Not Fired			Total
	No.	Per Cent of Total	Per Cent of Given Size	No.	Per Cent of Total	Per Cent of Given Size	
Lump (over 1¼ in.)	2	4.44	33.33	4	12.12	66.67	6
Lump (¾ in. to 1¼ in.)	3	6.67	42.86	4	12.12	57.14	7
Egg	0	....	....	1	3.03	100.00	1
Mine-run	*22	48.89	56.41	17	51.51	43.59	39
Screenings	18	40.00	85.72	3	9.10	14.28	21
Buck (anthracite)	0	....	....	1	3.03	100.00	1
Nut	0	....	....	1	3.03	100.00	1
No. 1 nut	0	....	....	1	3.03	100.00	1
No. 4 nut	0	....	....	1	3.03	100.00	1
Totals	45	100.00	....	33	100.00	....	78

* Three of these piles were a mixture of mine-run and screenings in about equal proportions.

TABLE 3
EFFECT ON SPONTANEOUS COMBUSTION OF SIZE OF COAL
QUESTIONNAIRE B

SIZE OF COAL	Fired			Not Fired			Total
	No.	Per Cent of Total	Per Cent of Given Size	No.	Per Cent of Total	Per Cent of Given Size	
Lump (2 in. or over)	1	1.32	1.96	50	20.83	98.04	51
Lump (¾ in., 1 in., 1½ in.	0	....	....	5	2.08	100.00	5
Egg	2	2.63	6.25	30	12.50	93.75	32
Mine-run	23	30.26	23.45	75	31.25	76.55	98
Screenings	44	57.89	51.16	42	17.50	48.84	86
No. 1 and No. 2 nut	1	1.32	3.85	25	10.42	96.15	26
No. 3 and No. 4 nut	5	6.58	27.80	13	5.42	72.20	18
Totals	76	100.00	....	240	100.00	....	316

These results are confirmed by the experience in England and John H. Anderson of Purfleet, England, says[†]:

[†] Trans. Inst. of Marine Engineers, June, 1918.

''When the coal is at a low temperature this oxygen absorption is very little; therefore, there is not much heat generated, and in many cases this little heat escapes to the atmosphere just as fast as it is generated. This is generally the case with the larger coals or coals free from small dust when there is usually a path here and there sufficient to allow the heat to get through to the surface by natural means.

''On the other hand, heaps may be composed of small coal, which may be so dense that there will not be sufficient apertures or paths for the generated heat to escape; the consequence is that this heat gathers, thereby increasing the temperature of the coal, and incidentally, due to the increase of heat, it increases the rapidity and capacity for further oxygen absorption in a given time, thus giving off more heat in a given time than when the heap was cooler.

''It will be seen from this that if a heap has a tendency to rise in temperature steps must immediately be taken to arrest this, otherwise the increase of heat will be so rapid after a time that it will not be possible to cope with it unless drastic measures are taken, such as to turn over the heap, or as it has happened before, letting it burn itself out.

''The liability of small coal to create spontaneous combustion is very pronounced, both from its size and also from it closing up the paths whereby the heat generated would otherwise escape freely to the atmosphere. I suggest that most of the oxidation is superficial and, therefore, if the smalls absorb more oxygen, they generate more heat in a given time than the larger coal, and therefore, small coal is more liable to fire than large coal, particularly if steps are not taken to let this heat out. This means that there is one safe height that must not be exceeded, but as there are other factors that must be taken into consideration at the same time, it would be almost impossible to fix this height for every heap. The height of pile can be increased above this safe height, providing means are taken to vent it. The more it is vented the higher the heap can be piled. Generally speaking, 12 to 14 feet is about as high as one should deposit small sized coals; 9 to 12 feet for unwashed mixed coals; for slack a great deal depends upon the composition. Two heaps of slack were allowed to rise 120 degrees before moving. These heaps gave considerable trouble at a height of 10 feet, but even when the height was reduced to 6 feet, there was a tendency to increase in temperature. My opinion of the cause of the trouble was bad washing of the material; thus after a shower, the shale-like material formed a plastic mass with the coal practically preventing any escape of heat.

''As a rule, little trouble is experienced in the storage of large coal, but one must be careful even with this, for in event of fire great difficulty will be experienced in putting it out owing to the ready access of oxygen for supporting combustion. Care should be taken not to make any smalls when depositing this coal, and if possible the coal should be selected that will weather best, otherwise that on top will crumble up and fill up the interstices underneath.

''The geological age of coal is a fair guide to its liability to heat, anthracite being the safest to store and lignite the most dangerous. A good guide is the weathering effect on a sample rather prominently exposed and occasionally moistened with water by hand, that which readily crumbles up being the most dangerous but, of course, a great deal depends on the composition of the coal, considering the impurities and foreign material that may be mixed with it."

The figures given in Table 4 indicate that a mixture of kinds and sizes increases the hazard; but these figures are by no means conclusive as to the effect of mixture of kinds of coal, for the questionnaires show that the mixtures which fired contained fine coal and this may have been the determining factor, rather that the mixture of different varieties of coal.

TABLE 4

RESULTS OF MIXTURE OF SIZES AND KINDS OF COAL

	Questionnaire *A*				Questionnaire *B*			
	Mixture of Sizes and Kinds		Same Size and Kind		Mixture of Sizes and Kinds		Same Size and Kind	
	No.	Per Cent	No.	Per Cent	No.	Per Cent	No.	Per Cent
Fired	31	69	14	31	23	30	52	70
Not fired	12	36	21	64	39	17	185	83

15. *Effect of Depth of the Pile.*—There is a rather common opinion that heating is most likely to occur about five feet from the surface. The table given on page 187 of Circular No. 6 of temperature observed by the Cleveland, Cincinnati, Chicago, and St. Louis Railroad at Hillary, Illinois, shows the highest temperature to occur at points five to ten feet from the top of the pile and that, in general, there is a gradual decrease in temperature below this maximum point.

J. H. Anderson says*:

> "From previous experience we found the warmest place to be between 6 and 8 feet deep from the surface; so from this we established a depth of 7 feet as the standard depth to record temperatures."

John Morison says†:

> "It is usual to find that heating commences at a depth of about 5 feet, and if left alone it will spread downward until the coal fires."

If coal is so piled that the fine portion stays on top of the pile and the lumps roll to the bottom, a point will occur in the pile where the air supply will be just sufficient to cause combustion of the fine coal but not sufficient to carry away the heated gases. Just where this point will be depends on the height of the pile, kind of coal, and method of storage. The replies to Questionnaires *A* and *B* as given in Table 5 indicate that the percentage of fires increases as the depth of pile increases. While the evidence seems to show that fires are more common in deep than in shallow piles, the reason for this is by no means certain, but any one of the following conditions may contribute to the result:

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* Trans. Inst. of Marine Engineers, Vol. 30, p. 83, June, 1918.

† North of England Institute, Feb. 9, 1918.

TABLE 5

EFFECT ON SPONTANEOUS COMBUSTION OF DEPTH OF COAL PILE

DEPTH OF PILE	Questionnaire *A*					Questionnaire *B*				
	Fired		Not Fired			Fired		Not Fired		
	No.	Per Cent of Given Depth	No.	Per Cent of Given Depth	Total No.	No.	Per Cent of Given Depth	No.	Per Cent of Given Depth	Total No.
8 ft. or less	2	33.33	4	66.67	6	26	18.44	115	81.56	141
8 ft. to 20 ft.	21	52.50	19	47.50	40	37	32.17	78	67.83	115
Over 20 ft.	21	67.74	10	32.26	31	5	41.67	7	58.33	12
Not stated	1				1	7				35
Totals	45		33		78	75		228		303

(1) There is less opportunity for the air to circulate through the pile and to carry off the surplus heat.

(2) The air and gases gradually rising through the pile and increasing in temperature as they do so, may finally reach the temperature of spontaneous combustion of the coal. This opinion is held by many, but if it is true, the greater number of fires should be found near the top of the pile.

(3) There will usually be increased breakage and an increased amount of fine coal which is the portion of the coal most liable to spontaneous combustion.

(4) There is greater difficulty in watching the pile and in detecting incipient heating. Consequently, fires develop in deep piles without detection more readily than in low piles.

16. *Effect of Quantity of Coal in Storage.*—Table 6 indicates that the liability to fires increases with the size of the pile, but the same considerations that make the evidence inconclusive for increased hazard with increased depth, apply here; also the term, *Quantity in Storage,* is often indefinite. Ten thousand tons stored in one pile thirty feet high is probably more of a fire hazard than the same amount spread out in a pile only five feet high; but this and other conditions of piling are not evidenced by the statements in the replies received under the heading, *Amount in Storage.* The difficulties of storing and watching a large quantity may increase the fire hazard, but a large quantity is not *per se* more dangerous than a small amount.

TABLE 6

EFFECT ON SPONTANEOUS COMBUSTION OF QUANTITY OF COAL IN STORAGE

QUANTITY	Questionnaire *A*					Questionnaire *B*				
	Fired		Not Fired		Total	Fired		Not Fired		Total
	No.	Per cent of given size of pile	No.	Per cent of Size	Total No.	No.	Per cent of Size	No.	Per cent of Size	Total Size
Less than 500 tons	2	50	2	50	4	35	18.61	153	81.39	188
500 to 1000 tons	5	50	5	50	10	11	24.44	34	75.56	45
1000 to 10 000 tons	18	66.67	9	33.33	27	26	40.62	38	59.38	64
10 000 to 100 000 tons	11	47.83	12	52.17	23	0	......	3	......	3
100 000 to 1 000 000	8	66.67	4	33.33	12	......	......	......	......	......
Over 1 000 000 tons	......	......	1	100.00	1	......	......	......	......	......
Not stated	1	......	......	......	1	3	......	0	......	3
Totals	45	......	33	......	78	75	......	228	......	303

17. *Effect of Methods of Piling.*—A study of the effect of the methods of piling indicates that the lowest percentage of fires occurs where the coal is stored by hand. It is, however, only the small low piles which are piled by hand, and as pointed out previously, the depth of the pile and to some extent the quantity of the coal piled are factors in the liability to spontaneous combustion. Any mechanical method of piling should be so devised that there will be the least possible segregation of the sizes of coal and the least possible breakage in handling. The coal should be distributed in layers over the whole

or a considerable part of the pile and not dropped at one point so as to produce a conical pile. In a conical pile the fine material is generally found at the center and the lumps at the outside and toward the bottom of the slope; this arrangement gives a passageway for air to enter the pile and to reach the fine coal near the center, which is the most liable to spontaneous combustion. A number of fires have started at a point within the pile where the flow of the air current was obstructed by the fine coal, thus establishing a condition in which the material most liable to spontaneous combustion was in contact with an excessive amount of oxygen. On account of the rapid oxidation of fine coal, the air current passing through such coal should be greater than that passing through larger sizes, while if the coal segregates in piling just the opposite condition is set up. To prevent breakage the clam-shell or other bucket should be lowered near to the surface of the pile before being dumped.

TABLE 7

EFFECT ON SPONTANEOUS COMBUSTION OF METHOD OF PILING COAL

METHOD	Questionnaire *A*			Questionnaire *B*		
	Total	Fired	Not Fired	Total	Fired	Not Fired
Shoveled by hand	11½	5½	6	201	35	166
Dumped from wagon	1	1				
Wheelbarrow	1		1	4	2	2
Dumped from truck				4		4
Wheeled scraper	2	2				
Dropped from car				9	3	6
Crane (locomotive)				13	7	6
Conveyor				5	4	1
Dropped from car on trestle	1	1				
Elevator				7	3	4
Bridge				2		2
Hydraulic	½*	½				
In hopper	1	1				
Not stated				58	21	37
Clam shell	7½	7½				
Crane	35½	17½	18			
Dodge storage system	1	1				
Belt conveyor	3	1	2			
Elevator	1		1			
Bridge	2	2				
Raising track on coal	7	3	4			
Underwater	1		1			
Not stated	2	2				
Totals	78	45	33	303	75	228

* ½ indicates that a storage pile was partly piled by one method and partly by another.

18. *Causes of Fires.*—The question, "What in your opinion was the cause of the fire?" brought forth a number of reasons which are listed in Table 8 for the purpose of expressing popular opinion on the subject.

TABLE 8

CAUSES OF FIRE

CAUSES OF FIRE	Questionnaire *A*	Questionnaire *B*
Outside source of heat or aid to combustion in contact with coal		
Ground saturated with oil	2	....
Wood in coal	....	7
Heat from boiler	....	3
Litter from stables	....	1
Rust from embedded steel rails	....	1
Moisture or weather conditions		
Rain	2	4
Blanket of snow	1	....
Wet coal	....	7
Contact wet and dry coal	....	1
Wet ground or water under pile	2	1
Weather condition when coal was unloaded	2	....
Sun	....	2
Sulphur	3	9
No reason evident except coal itself or method of piling		
Lack of ventilation	....	2
Air circulation	3	....
Segregation of sizes	8	1
Fine coal	....	1
Mixture of coal	4	2
New coal piled on old coal	1	....
Pile too deep	2	1
Quality of coal	....	1
No opinion	15	31
Totals	45	75

19. *Extent of Fires When Discovered.*—The extent to which the fire was allowed to progress before discovery has been tabulated, not because it tells anything about the cause of the fire, but because it serves as an indication of the attention given the storage pile:

TABLE 9

EXTENT TO WHICH HEATING HAD PROGRESSED

CONDITION OF FIRE	Questionnaire *A*	Questionnaire *B*
Odor only	0	3
Smoke	26	39
Ablaze when exposed	7	13
Ablaze	12	20
Totals	45	75

If precautions had been taken by the ordinary methods of watching for fires and by being prepared to handle them promptly, none of the fires should have reached the point of blazing. If thermometer readings are taken, the heating of the pile can be stopped before it reaches the point where smoke due to combustion is given off. Temperature readings are not taken nearly so often as they should be in watching a storage pile but the following reports are of interest, as showing very imperfectly some relation between observed temperature and the other evidence of firing in a coal pile. The indefinite use of the term, *fire,* renders any generalization from these figures impossible as *fire* and *heating* are too often used synonymously.

TABLE 10

TEMPERATURE OBSERVED IN STORAGE PILES

No Fires Observed		Fires Observed	
		132° Fahr.	Short time before fire
145° Fahr.	Coal moved	180°	Smoking
69°-82°		160°	Smoking
120°	Coal moved	140°	Before smoke seen
		180°	After smoke seen
		185°	Smoking

Temperature readings were not taken in any one of the 75 piles where fires occurred as noted in Questionnaire *B* and in only one case of the 303 reports of storage was there a temperature reading taken. This was 125 degrees Fahr., in the center of a storage pile. When the coal was removed from above this point, the pile cooled off.

20. *Danger Temperatures in Coal Piles.*—One railroad advises loading out the coal if the temperature reaches 100 degrees, but as the temperature in the sun in summer over a large part of the United States is frequently above 100 degrees, this regulation would be impracticable. Moreover, summer is the best time to store much of the coal on account of production and transportation conditions.

J. H. Anderson[*] says: "Ninety degrees Fahr. was made a warning temperature. One hundred degrees Fahr. was adopted as a danger reading at which point a trench was dug in the pile."[†]

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[*] Trans. Inst. of Marine Engineers, Vol. XXX, June, 1918.

[†] See page 36 for method adopted by Mr. Anderson to arrest rise in temperature.

In Circular No. 6, 140 degrees was given as a warning temperature; later studies indicate that if the temperature reaches 140 degrees the pile should be carefully watched and if the temperature continues to rise rapidly to 150 or 160 degrees, the coal should be moved as promptly as possible and the coal thus moved should be thoroughly cooled before being replaced in storage. If the temperature rises slowly, although the pile should be carefully watched, it is not necessary to begin moving the coal at so low a temperature as when the rise is rapid, for the temperature may recede and the danger be passed.

21. *Detection of Coal Pile Fires.*—The common methods of detecting the heating of a coal pile are:

(1) By watching for evidences of steaming in the pile.

(2) By noting the odor given off; bituminous or sulphurous odors are evidences of heating.

(3) By noting places where snow on a pile has melted.

(4) By inserting an iron rod in the pile, and by noting its temperature with the hand after withdrawal.

(5) By inserting thermometers into the pile and reading directly.

(6) By using a pyrometer or plates connected with an automatic recording device.

The first three methods are so self-evident in their application that it is unnecessary to discuss them in detail, but with a large pile, and particularly one where the heating is distant from the surface, a fire may reach an advanced stage without being detected by surface indications.

Method No. 4, by which the temperature of an iron rod is noted with the hand, is a simple test, and one well-adapted to piles not over eighteen to twenty feet deep. By this means a janitor using a poker may keep informed as to the condition of the comparatively small amounts stored in house or apartment basements.

Temperature readings with a thermometer or pyrometer furnish by far the best and most reliable method for keeping informed on the exact condition of a coal pile.

To get the temperature of the inside of a coal pile it is necessary first to provide an opening into which a thermometer or a pyrometer

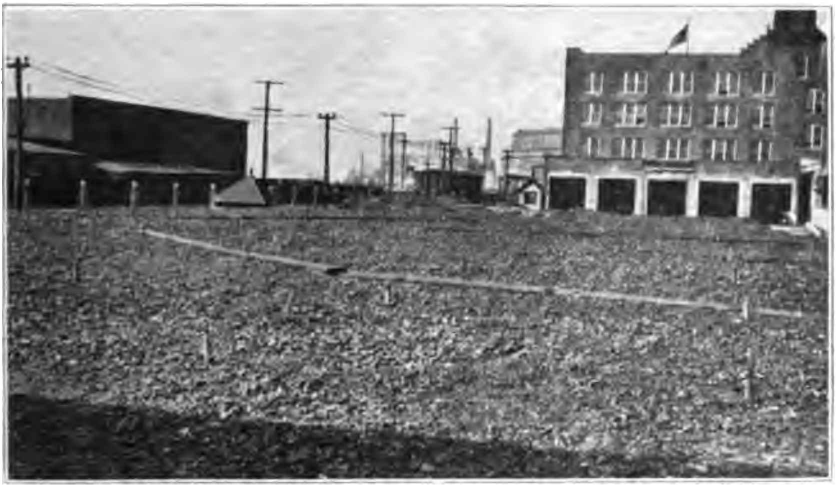

FIG. 1. PILE OF SCREENINGS WITH TEMPERATURE TUBES, CLOSED AT UPPER ENDS BY WOODEN PLUGS

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may be inserted. Such openings may be made after the coal is in storage by driving pipes into the pile, but it is easier to place these pipes when the coal is being stored. Pipes left permanently in a pile are a disadvantage as they interfere with the appliances used to remove the coal. Instead of leaving the pipe in the coal pile it is sometimes necessary only to drive it and then withdraw it, the hole remaining open sufficiently to permit the insertion of the thermometer. To prevent the hole from filling with coal, an inverted funnel of paper is used in Canada.

Such pipes as shown in Fig. 1 should be plugged at the upper end so as to exclude the outside air, for if ventilation is allowed through these pipes, a correct temperature reading of the interior of the coal pile is not obtained.

If an iron pipe of small diameter is forced into the coal pile and is then moved up and down, the small amount of coal which has entered the pipe is removed. To prevent the pipe from filling up with coal as it is driven into the pile, a pointed plug may be placed in the end of the pipe and when the pipe has been forced into the pile to the desired depth the plug may be driven out by means of a rod inside the pipe. Before inserting the thermometer the pipe should be pulled up a slight distance so that the thermometer reading may give the temperature of the coal and not that of the iron pipe.

One answer to the questionnaire described a method of making an observation hole by running a rod into the pile and then moving it around in a circle to form a hole sufficiently large and open for the insertion of a thermometer.

The Arthur D. Little Company, Incorporated, of Boston, makes the holes with a regular coal auger drill which is described as follows:

> "These augers are regular mine auger drills and the total length of the auger can be extended indefinitely by sectional parts fitted with screw threads. It is preferable to have a handle for turning the drill, although this can be very easily accomplished by means of a Stillson wrench."

J. H. Anderson* describes a method that he used with success for watching and regulating the temperature of coal piles. A storage pile of about 16 000 tons composed of a variety of coals which would not be stored under ordinary circumstances was chosen for experimental purposes, the depth of the pile varying at different points. The coal was stored on marshy ground above a ditch which had been filled with ashes to the level of the surrounding marsh. Some of the coal was deposited during very hot weather and some during heavy rain. Some was dry when unloaded from the steamer and some soaking wet. The conditions thus seemed to be particularly unfavorable and extra care was exercised in watching the pile. Temperature readings were taken at fourteen different places in the pile nearly every day at a depth of seven feet from the surface, as previous experience had shown that the warmest place was between six and eight feet from the surface. This standard depth was also adopted for comparing the results obtained in piles in other parts of the county. Occasional check readings were taken at every foot depth in the pile. The temperature tubes ¾ inch to 1 inch in diameter were driven to the bottom of the coal and were long enough to project two or three feet above the pile. Each tube had a numbered metal label on it for purposes of easy identification. In addition to the temperature pipes about fifty "vent" pipes were placed in the pile, not to ventilate the whole pile, but to draw off hot gases from local points. These pipes were 3 inches to 4 inches in diameter and 8 feet long. About 8 inches along the length four holes were punched from the outside with a square tapered punch to about ¾ inch; thus leaving a burr which prevented the coal from going down inside the pipe. To facilitate driving into the coal pile, the ends of the pipes were flattened chisel-shaped with an aperture about one-half inch left to prevent an accumulation of water at the bottom of the pipe and to permit the escape of air and gases. The pipes were driven to a depth of seven feet in the coal, leaving one foot projecting above the surface. A distinctive number was painted on each so that temperature readings could be properly accredited.

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* Trans. Inst. of Marine Engineers, June, 1918.

By means of periodical temperature readings a close watch was kept on the pile. Ninety degrees Fahr. was made a warning temperature and when this temperature was observed at any place, four temperature pipes were driven north, south, east, and west about ten feet from the warm pipe. The next day readings of the four pipes were carefully noted and the one showing the highest temperature was made the center and other pipes were put down around it. When the warmest spot was found in this way, a vent pipe was put in at this point and the rise in temperature was generally arrested. The smaller temperature pipes were then removed. One hundred degrees Fahr. was adopted as a danger reading and if the vent pipe failed to arrest the temperature and it reached 100 degrees, a trench one foot deep was dug. If the daily readings were 100 degrees for, say three days, a spot would be trenched three feet deep. The danger temperature originally adopted was 95 degrees Fahr., and on four separate occasions trenching was done at one place, about 10 000 tons of material being removed. As the readings in this pile at no time reached 100 degrees Fahr., the trenching probably would have been unnecessary if additional vent pipes had been used. The coal was 16 feet deep at this point.

A somewhat similar method used by the Boston and Albany Railroad is described by S. Bisbee, Fuel Supervisor, as follows:*

> "At one point 2-inch flues sharpened at the end were forced down to the bottom of the pile and worked around, then withdrawn, leaving a hole 3 to 4 inches in diameter, the holes being spaced 5 feet apart. If there is any tendency to heat, the number of holes is increased. Little trouble from spontaneous combustion. One fire started around a wooden pier, and another fire started in a high pile 10 feet from the bottom. Coal below this point found to be cool and no further trouble. Other fires occurred where piles had been placed on cinders. In no place did we have to dig out the coal for a distance of more than 40 feet, showing the spontaneous combustion was due to some local cause and that being removed there was no further trouble."

22. *Appliances for Reading Temperatures.*—

Thermometers

The simplest form of thermometer for obtaining the temperature inside such temperature holes is an armored maximum registering thermometer, as illustrated in Fig. 2.

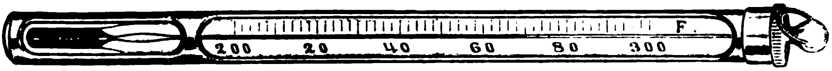

FIG. 2. MAXIMUM TEMPERATURE THERMOMETER — ARMORED TYPE

Thermostats

The Illinois Central Railroad has used at several coal chutes, thermostats which were placed on the bottom plates of the coal bins so that if the coal heated in the bottom of a bin an alarm would be rung. These were installed in connection with an automatic hot journal alarm system furnished by the Western Fire Appliance Company of Chicago.

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* "Storage of Coal by Railroads during 1918," by H. H. Stock. Inter. Ry. Fuel Assoc. Proc., 1919.

Recording Thermometers

A recording thermometer, made by the Foxboro Company, for obtaining the temperature of a coal pile, is illustrated in Fig. 3. It consists of a recording pen that is operated by the vapor tension from a volatile liquid placed in a bulb at the end of a long flexible armored tube. This capillary tube is usually about five feet long but practically any desired length may be used. To register accurately the temperature of the hub must be about that of the atmosphere. The instrument can be equipped with an electrical alarm so that a bell or other means of signal will be operated if the temperature rises to a predetermined danger point.

A cheaper installation consists of a dial thermometer as shown in Fig. 4, similarly connected to a bulb by a protected capillary tube. This form can also be arranged to give warning automatically when a given temperature is reached.

The Zeleny Thermometer

The Zeleny Thermometer system which is extensively used for observing the temperature of grain in storage tanks or bins has been adopted for observing the temperature of coal in storage in silos, pockets, or other storage bins.

The apparatus consists of a reading instrument and a switchboard as shown in Fig. 5. From the contact points of the switchboard, wires lead to the various points in the bins where the temperature is desired. The contact pins are properly labeled and when the switch lever is placed in contact with any one of these, the reading instrument indicates the temperature. In this way the temperature of many stations may be determined in a short time. The action of the instrument depends upon the thermo-electric properties of the metals used in the construction of the circuits. The wires leading into the coal are enclosed in heavy steel conduits so as to withstand the pull of the coal when the bins are being emptied. These steel conduits are supported at the top but are free to swing at the bottom. Naturally when there is coal in a bin the conduit is held stationary by the coal. When the bin is empty the lower end of the conduit may be tied by a small rope to the bottom of the bin so as to keep it from swinging when the bin is being filled. In coal silos or bins of small diameter it may be sufficient to know the temperature of the coal along the walls or other supports in the bins; in this case the swinging steel conduits could be eliminated, and stations fixed at several points along walls or supports.

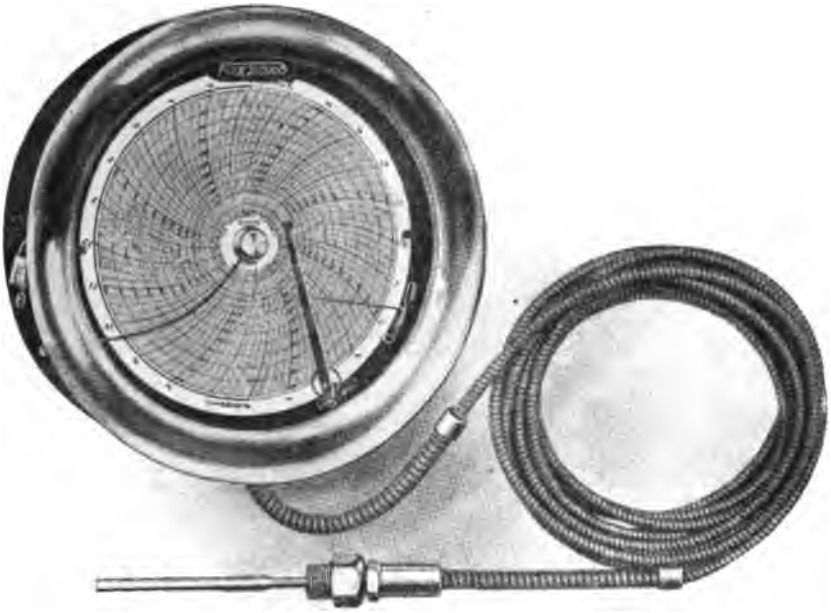

Fig. 3. Recording Thermometer — Long Distance Type

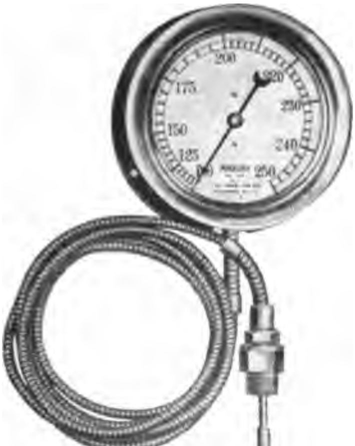

Fig. 4. Indicating Thermometer — Long Distance Type

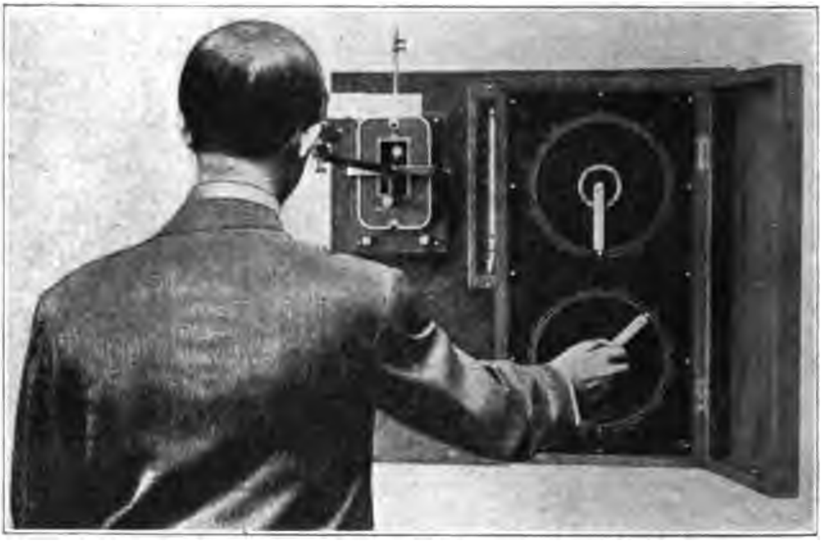

Fig. 5. Zeleny Thermometer System — Reading Instrument and Switch Board

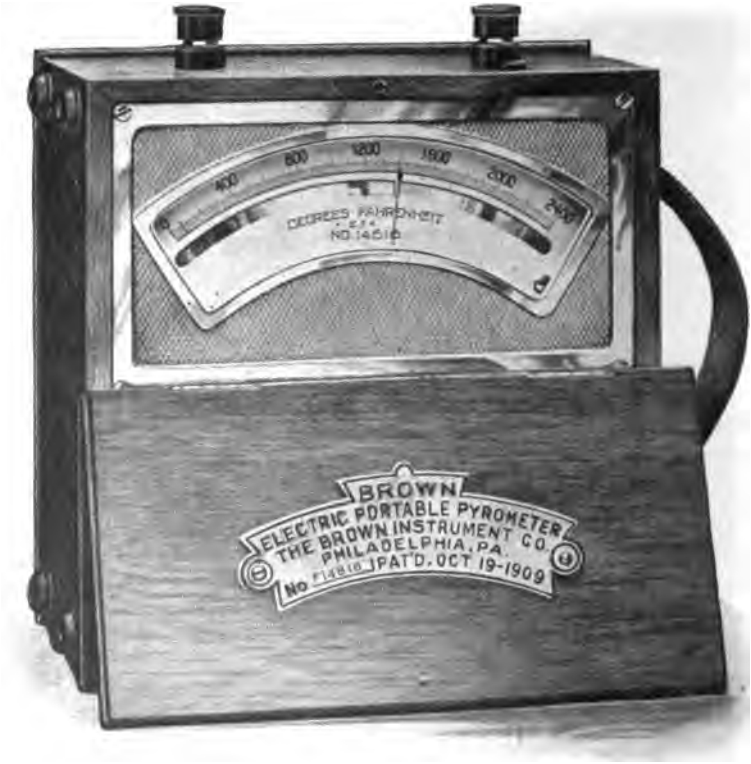

Fig. 6. Indicating Pyrometer — Millivoltmeter Type

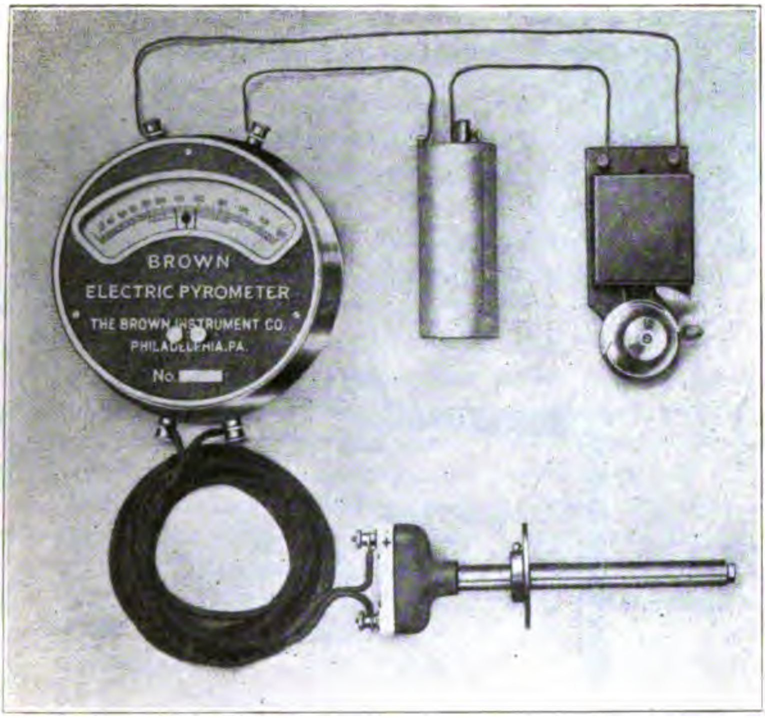

Fig. 7. Indicating Pyrometer with Alarm Attachment

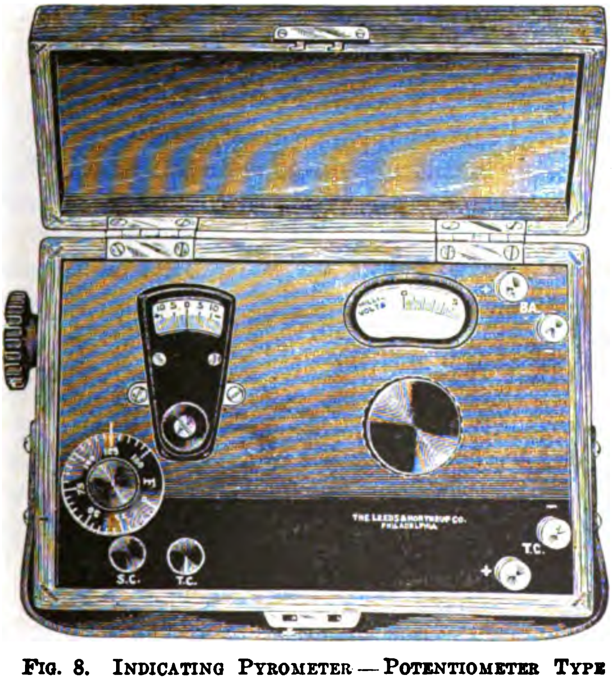

Fig. 8. Indicating Pyrometer — Potentiometer Type

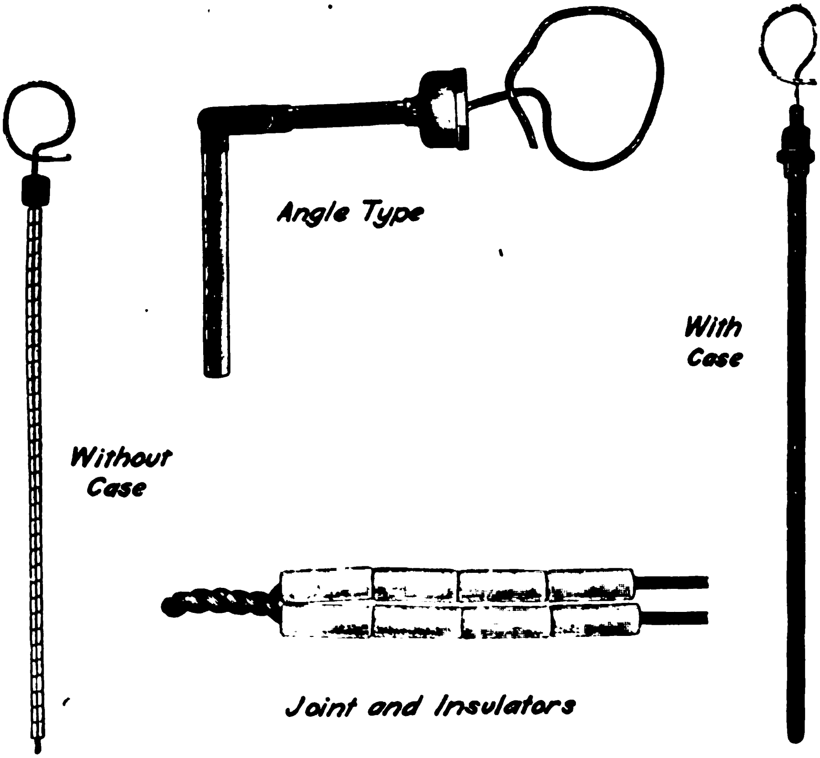

FIG. 9. BASE METAL THERMOCOUPLES FOR PYROMETERS

Pyrometers

Fig. 6 shows a portable electric pyrometer that has been used for obtaining the temperature of coal piles and Fig. 7 a similar alarm pyrometer.

A recording pyrometer may be connected with a rotary switch having any desired number of points, each point suitably connected with a separate thermocouple that may be placed in any part of the coal pile.

An indicating pyrometer of the potentiometer type for use with thermocouples is shown in Fig. 8. This reads in millivolts and it may be used with most types of thermocouples. The cold junction compensator on the instrument is also calibrated in millivolts. With this instrument it is necessary to use a transfer table of millivolts and temperature for the particular thermocouples used. The instrument will cover a range of approximately zero degrees to 340 degrees Fahr. Fig. 9 illustrates the type of base metal couple for use with this instrument.

Thermocouples and Potentiometers

Fig. 10 shows a method of observing temperatures in a coal pile of 10 000 tons described by T. W. Poppe.* Observations were taken at points noted in the plan inside of one-inch wrought iron pipes welded to a point at the ends which were driven into the pile. The exposed ends were fitted with self-closing caps to prevent the entrance into the pipes of anything that might interfere with the introduction of thermocouples. Fifteen portable thermocouples were used and the wiring from these extended to a pole centrally located in the coal pile from which a permanent wire extended to the engineer's office. The switches in the office were numbered and lettered to correspond with the pipes in the coal pile. An attendant placed the thermocouples in the pipes 1 to 15 row *A* and the readings were taken at the switchboard. As soon as the last couple had been placed in 15 *A*, the attendant began to move thermocouple 1 *A* to 1 *B*, etc., in numerical sequence, the time elapsing between the placing of 1 and 15 being sufficient to allow the couples to become heated to the temperatures in the several pipes. A recording pyrometer can also be used with the arrangement outlined. If a temperature of 250 degrees was indicated at any point, the nearby coal was at once moved to a point

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* Power. Nov. 5. 1918.

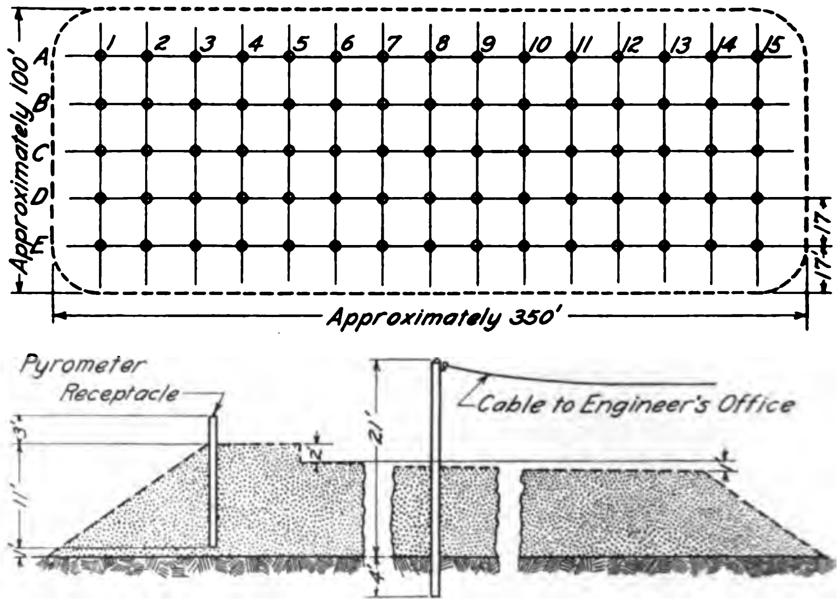

FIG. 10. PLAN AND SECTION OF COAL PILE SHOWING ARRANGEMENT OF RECEPTACLES FOR PYROMETERS

near the place of consumption. In removing the coal from this pile to the boiler plant it was taken off in layers two feet thick over the whole pile, a gradual slope being maintained as shown to facilitate the use of a wheelbarrow.

Mr. G. J. Congdon, Supervisor of Fuel of the Chicago Great Western Railroad, has described the use of a thermocouple and potentiometer by his road as follows:

> "The machine was purchased after the coal was on the ground and in order to get the thermocouple down into the coal it was necessary to drive old flues into the piles about 15 feet apart and in addition we have a portable, jointed pipe which can be driven into the piles at any place desired where the temperature may be thought to be rising. These pipes are perforated at the bottom and covered at the top in order to keep the circulation down as low as possible.
>
> "By means of the blank form (Fig. 11) which is filled out on the ground, a careful check is kept to see whether the temperature is rising or falling. It is a very simple matter to see how the coal is storing as the temperature can be compared from week to week and where there is an inclination to rise consistently we proposed to dig out that particular spot and use the coal at once in order that

PYROMETER TEST RECORD ——————— STORAGE COAL

Date	Pile Numbers																										

FIG. 11. TEMPERATURE RECORD BLANK USED BY CHICAGO GREAT WESTERN RAILROAD

it may not spread to the rest of the pile, but we have never had to remove any of our coal on account of heating.

"The cables we use have five couples but it was never necessary to use but three of the couples as we had our coal piles only 10 to 12 feet high. The temperatures were taken by inserting this cable into the flue driven to the bottom of the coal or nearly so and leaving it to adjust itself to the temperature in the pipe, taking care meanwhile to keep the top of the pipe covered as much as possible. This takes only a few seconds. By changing the terminals on the cable to the potentiometer we could ascertain the temperature at the bottom, five feet from the bottom and ten feet from the bottom or by graduating the cable you could insert the same to any depth desired although on the whole I think but one temperature is about all you could get from the flue and that would be the highest one.

"One of the bad features of the machine is the fact that it is very hard to get it even on top of a coal pile and unless it is level there is liable to be quite a difference in two readings even taken on the same day. I used a small spirit level for this purpose satisfactorily."

23. *Time when Fire Was Noted.*—The length of time the coal was in storage before fire was discovered is shown by the graphs, Figs. 12 and 13 where the number of fires and the time in weeks are the coördinates. These graphs show that most of the fires occurred in the first three months of storage. After that the hazard decreased as the time increased. This result is in agreement with the Chicago fire observations (see page 63), except that the peak of the graph

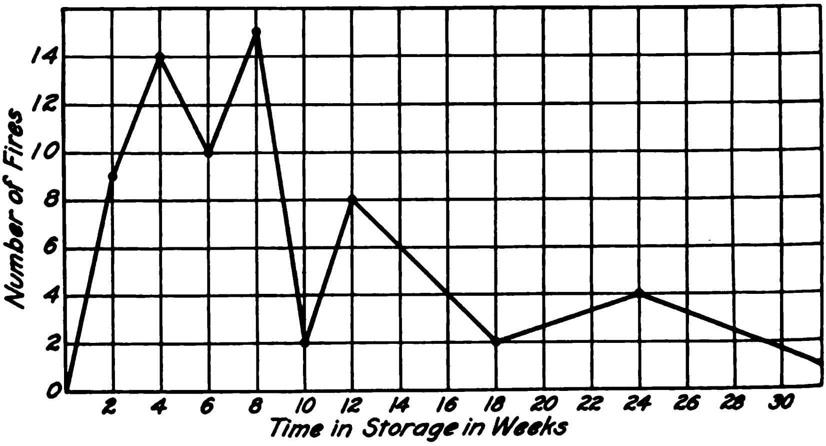

FIG. 12. GRAPH SHOWING LENGTH OF TIME COAL WAS IN STORAGE WHEN FIRE WAS DISCOVERED (QUESTIONNAIRE *A*)

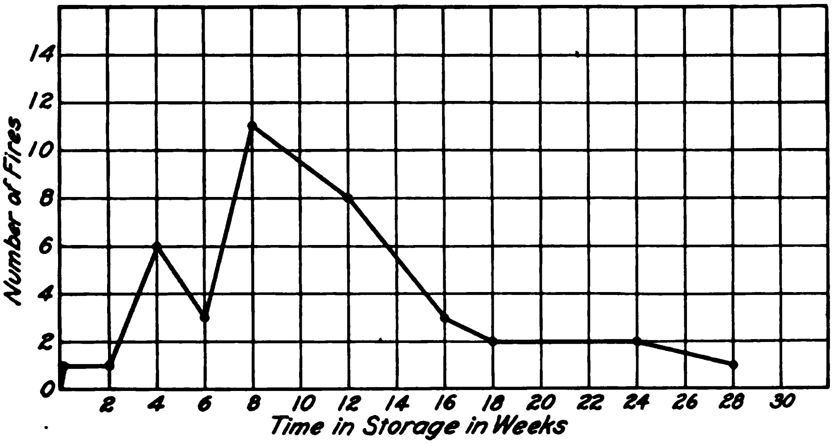

FIG. 13. GRAPH SHOWING LENGTH OF TIME COAL WAS IN STORAGE WHEN FIRE WAS DISCOVERED (QUESTIONNAIRE *B*)

occurs at eight weeks for cases reported in answers to Questionnaires *A* and *B*, while for the Chicago fires it occurs at twelve weeks.

These results confirm the opinion expressed in Circular No. 6 that, during the first three months after storage, particular attention should be given to watching a coal pile, and while the danger is by no means past after three months, the liability to fire seems to decrease rapidly. In this connection it should be noted that much of the coal involved in the answers to Questionnaires *A* and *B* was stored during the hot summer months so that the initial temperature was often high, which fact would tend to hasten spontaneous combustion. Some of those who store large quantities of coal do not feel that a pile is entirely safe until it has been in storage through one summer, but the experience of the Commonwealth Company quoted on page 23 shows that fires may occur after a pile has passed one summer.

J. H. Anderson says:*

> "As a rule the greatest danger is up to about three months from the time of taking the coal from the pit."

24. *Reducing Temperature and Extinguishing Fires in Coal Piles.*—The following methods are employed for reducing the temperature in a coal pile.

---

* Trans. Inst. of Marine Engineers, Vol. XXX, p. 92, June, 1918.

Moving the Coal

The most effective method of combating a tendency to fire in a coal pile is by turning over the coal and exposing it to the air so that it may be thoroughly cooled. Care must be taken in exposing hot coal to the air, for, if the temperature is too high, as soon as the hot spot is opened out the mass will burst into flame and the fire spread very rapidly. Therefore, if there is evidence of a high temperature the spot should not be opened out unless there are ample appliances at hand immediately to move the hot coal or water sufficient to put out any fire that may start and thoroughly to cool off the mass.

Whenever the fire has reached the stage where the coal is actually ablaze, it may be necessary to use water but, in general, water should not be used if it can be avoided.

The smoke and fumes given off by the burning coal make the work of moving a coal pile very unpleasant, especially in a confined space, and the workmen may become dizzy. This difficulty was overcome at a fire in the basement of the Manual Arts Building of the public schools of Charles City, Iowa, during the spring of 1916,* by installing an electrically driven fan in such a way as to draw the smoke out of the basement so that the workmen could shovel the coal. The fan also drew fresh air over the shovelers, kept the space clear of smoke, and prevented the smoke from entering the building. When the fire was reached the smoldering coal was removed. The use of water on a previous occasion is said to have added to the trouble, but the reason is not stated.

Use of Water

The opinion is very commonly held that although fire in a coal pile is apparently extinguished by water, another fire is apt to break out in the same place. One reason for this was seen in at least one of the Chicago fires which were visited during the summer and fall of 1918. It was noted that as a result of the heating of the coal, a coating of tar had sealed the coal together in such a way that the seat of the fire at the center of the mass could not be reached by water. A coal pile also may have so much fine coal in it that the water can not penetrate to the point of the fire.

The ineffectiveness of a continued wetting of the surface of a coal pile in keeping down a fire was demonstrated by the Aurora,

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* Power, Vol. 44, p. 567.

Elgin, and Chicago Railroad at Batavia, Illinois, in connection with a storage pile of 12 000 tons of Warrick County, Indiana, mine-run which gave trouble from heating during the summer of 1918. A pipe (see Fig. 14) was suspended over the pile of coal and to this pipe were attached nozzles or sprinklers with which the coal was sprinkled continuously for six or eight weeks.

The chief engineer of the plant reports that as soon as the water was turned off the fire started up again. He also states that in his opinion the fires were never thoroughly quenched throughout the piles,—that is, the water reached only the surface. The system was discontinued late in November to prevent freezing, and a number of fires were reported in the piles during the winter, so that it became necessary to reclaim a great deal of the coal during February and March.

A numbef of instances have been cited where perforated pipes were said to have been driven into heating piles and water injected into the pile at some depth through these pipes. There have been no personal observations of such an appliance upon which to base any conclusions as to the results of this method, but of six companies said by a manufacturer to be using the method successfully, one says that it was a complete failure, two have not tried such an appliance, one has not given it a sufficient trial to express an opinion, one said the appliance failed because tar clogged the nozzle, but thinks the apparatus would operate on certain kinds of coal, and one only had found it successful.

In England those who store coal have reached the same conclusion in regard to the use of water and J. H. Anderson says:*

> "In case of a fire in a heap of coal, although plenty of water should be available to quench out a fire if flames are seen issuing, still common sense must be used before we do even this, it being better to dig all round the fire; then, if possible, remove the hot coals away from the heap; then quench the material there.
>
> "Plenty of warning will be given and the spot localized before there is any actual danger if a systematic method of temperature readings is carried out. In case of overheating, the seat of heating would be dug out. Great difficulty would be experienced to get water to a fire in the middle of a heap, as the fire would cause a certain amount of the coal to melt and form a coked mass.
>
> "Of course, if the fire was in a receptacle that could be flooded out, such as a storage bin or a vessel's hold, it may be the best plan to flood; but I certainly should not do this except when there was an actual fire that could not be treated otherwise."

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* Trans. Inst. of Marine Engineers, p. 92, June, 1918.

It is evident that the exact effect of moistening coal requires further examination as the results of experiments thus far performed and the opinions expressed by different experimenters are not in agreement.

In Technical Paper No. 16 the authors say:*

> "The effect of moisture and the effect of sulphur on the spontaneous heating of coal are questions on which there has been a great deal of discussion and much difference of opinion. Very little experimental evidence has been brought to bear on either of the questions, and certainly neither is as yet settled. Richters has shown that in the laboratory dry coal oxidizes more rapidly than moist; but the weight of opinion among practical users of coal is that moisture promotes spontaneous heating. In not one of the many cases of spontaneous combustion observed by the authors, as representatives of the Bureau of Mines, could it be proved that moisture had been a factor. Still the physical effects of moisture on fine coal, such as closer packing together of dust or small pieces, may in many cases aid spontaneous heating."

In Technical Paper 113† the authors conclude:

> "Heat is produced by wetting dry coal or a partly dried coal containing less than its normal percentage of inherent water. The relative quantity of heat generated depends upon the kind of coal and its deficiency in inherent water as referred to its maximum normal content. In other words the thermal effect of wetting varies directly as some function of the relative vapor pressure deficiency in the coal. The results of calorimetric determinations of the heat of wetting for different coals and for various percentage of water content are tabulated and illustrated by diagrams in the paper. Sub-bituminous coal from Wyoming that had been dried produced, by complete wetting, 19.2 calories of heat per gram of dry coal; brown lignite from North Dakota, 25.5 calories; bituminous coal from Franklin County, Illinois, 6.8 calories; and bituminous coal from the Pittsburgh bed, one calorie.
>
> "On the basis of known specific heats of these coals, if the values of the saturated coals are taken and it is assumed that no heat is lost to the containing vessel or to excess water, or by radiation, the heat developed would raise the temperature of the different coals as follows:

	Degr. C.
Wyoming coal	43
Brown lignite from North Dakota	64
Franklin County, Illinois	20
Pittsburgh bituminous	4"

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* U. S. Bureau of Mines, 1912, "Deterioration and Spontaneous Heating of Coal in Storage," by H. C. Porter and F. K. Ovitz.

† U. S. Bureau of Mines, 1915, "Some properties of the Water in Coal," by H. C. Porter and O. C. Ralston.

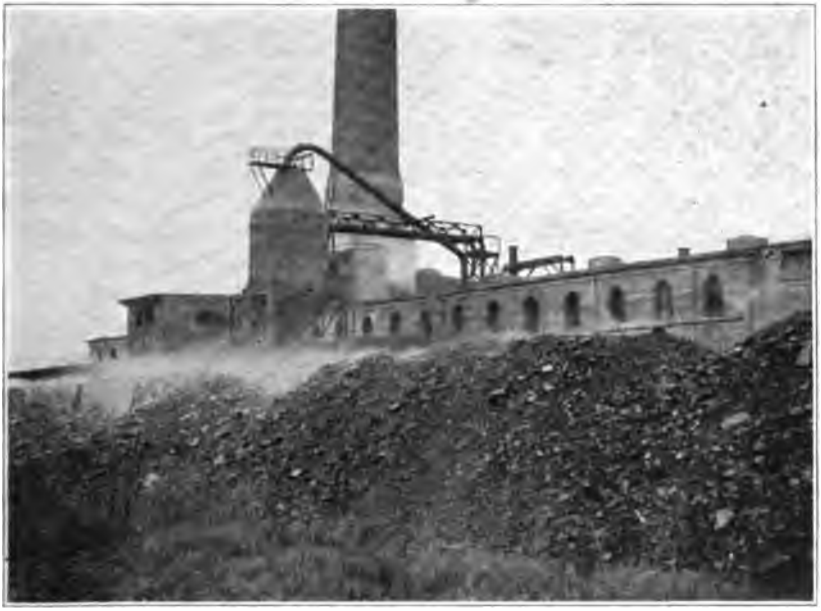

FIG. 14. SPRINKLER SYSTEM USED BY AURORA, ELGIN, AND CHICAGO RAILROAD COMPANY, BATAVIA, ILLINOIS

In Technical Paper No. 172* the authors conclude:

> "The experiments showed that with Illinois coal thoroughly dried the rate of oxidation at ordinary temperatures was greater than with a comparative sample of moist coal. On the other hand a thoroughly dried sample of Pittsburgh coal oxidized at a slower rate than a comparatively moist sample of the same coal. This difference between the two coals probably explains the discrepancies in the observations of different experimenters. Richters found that a German coal absorbed more oxygen when dry than when moist. Mahler, investigating a French coal, and Graham, investigating an English coal, found that moist coal absorbed more oxygen than dry. Evidently the rates of oxidation of different coals are not affected uniformly by moisture."

The investigators named worked with small quantities of coal in the laboratory and used extreme conditions. Under actual conditions of storage both the coal and the air always contain moisture. Hence it seems doubtful whether water, other than the excess that actually wets the coal plays an important part in the rate at which coal oxidizes at the lower temperature, with consequent increase in the danger of spontaneous combustion. The experiments conducted on a working scale by Fayol, who could find no influence of wet weather on spontaneous combustion, and by the New South Wales Commission, which found that actual wetting of the coal produced a cooling effect during storage, tend to confirm this idea.

The authors of Technical Paper 172 summarize their conclusions as follows:

> "However, the opinion among coal shippers and consumers that there is more danger of spontaneous combustion during warm, wet weather than during dry weather may have another basis, the physical changes brought about by wetting the coal on the surface of the pile. Such wetting reduces the proportion of voids or open spaces in the mass. If the coal is divided into particles fine enough, the water will fill the voids completely and be held there by capillary attraction. Such a mass of coal and water on any part of a pile would block the passage of air at that place. As a result the conditions of ventilation in the pile before the wetting would be changed, so that, is some instances, the heat generated by the gradual oxidation of the coal would be retained until the temperature of ignition was reached.
>
> "For instance in a pile of coal formed in the usual manner with the fines at the top because of the rolling down of larger particles there would be a mass overlain with an impervious cover through the wetting of the outside surface. This cover would prevent air circulating by convection. Under such conditions oxygen would diffuse, as the coal absorbed it, from the lower parts of the pile to

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* U. S. Bureau of Mines, 1917, "Effect of Moisture on the Specific Heating of Stored Coal," by S. H. Katz and H. C. Porter.

the covered part. The heat produced would be retained in the pile, and the temperature of the coal would increase at a rate dependent on the rate of oxidation alone; ignition temperature would readily be reached, and a spontaneous fire produced. The conditions described have been approximated to a degree in many storage piles of coal. In those piles moisture had a decided influence in the production of spontaneous fire."

J. B. Porter* summarizes the effect of moisture as follows:

"From the Reports of the Royal Commission on Coal Cargoes in England (1876) and in New South Wales (1897) one might conclude that coal containing much moisture would be likely to heat badly; yet out of 26 persons, who in 1876 testified to the injurious effects of moisture, 25 admitted on cross-examination that they were simply repeating hearsay, and the other remaining witness was not available for cross-examination; furthermore, although the bulk of the testimony in 1897 was apparently to the same effect, the conclusions of the Commission did not give it much weight.

"One would naturally expect that a coal containing moisture would be retarded in its heating because, until all the moisture has been evaporated, the temperature cannot rise above 100 degrees C. Yet, on the other hand, the steam percolating through the surrounding mass, and condensing in the cooler parts, will heat as well as moisten them, and may thus tend to hasten oxidation in those parts.

"It would seem that the experiments (of Richters) definitely prove that moisture hindered the absorption of oxygen of the coal in question, but this is not in accordance with the results of recent experiments by Porter and Cameron, and furthermore, there is no doubt that moisture will increase the rate of oxidation of pyrite; and whether the net results will be an increase or decrease in the final temperature must depend on the amount of pyrite present and on the amount of moisture."

Fayol experimented with:

1. Fresh fine coal.
2. The same coal dried in ovens at a temperature not exceeding 40 degrees.
3. The same coal dried but sprinkled to make it damp but not wet.

A number of piles of each kind were placed under similar conditions and temperature observations were made every day for several months. The temperature changes were found to be practically the same in all the piles and in no case did the temperature rise above 50 degrees.

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* "An Investigation of the Coals of Canada," Extra Vol., Canadian Dept. of Mines.

Parr and Kressmann* studied dry and wet coals at temperatures of 40, 60, 80, and 150 degrees C. Without exception in these tests wetting the coal increased the activity as shown by the ultimate temperature. It must be remembered, however, that these coals were stored at high temperatures which were raised by external heat.

J. B. Porter says:

> "A study of their results would seem to show that the wet coals did not heat on their own account until this externally applied heat raised them above 80 degree C., which is fatal to many coals."

J. B. Porter concludes his study as follows:

> "In conclusion it may be said that in all probability the temperatures of ordinary coals under ordinary conditions of storage are not raised to any appreciable extent by moisture. The question naturally arises, what was the basis of the once prevalent belief that moisture was an important factor in spontaneous heating?
>
> "This belief is, no doubt, chiefly due to the confusion of cause and effect on the part of persons who have discovered fires in coal storage. It is commonly observed that fires or hot spots in the pile are discovered shortly after rain storms, and that nearly always a hot spot is surrounded by damp or wet coal even if the main part of the pile is dry. The first case is easily explained by the fact that dry coal is so poor a conductor that the surface of a pile may show no indication of a hot spot or even an incipient fire in the interior. A rain storm would, however, provide moisture enough to soak into the pile, and this moisture on approaching the hot spot would be turned into steam which would work its way back to the surface and be observed, thus attracting attention to the hitherto unsuspected heating. The second explanation is equally simple. Air dry coal always contains some moisture, and in lignitic coals there is also a very considerable amount of combined water. In the case of a hot spot in the interior of a pile this moisture is driven off, either escaping at the surface as steam, or condensing on the cooler coal in the neighborhood. Added to this there is, of course, an actual formation of water when the hydrogen constituents of coal are oxidized.
>
> "As an illustration of the second case it may be noted that during the experiments of the author at Outremont and Glace Bay vapor or condensed moisture was always noticed in the observation tubes in the neighborhood of hot spots even when the temperature was far below the boiling point."

The following extract from Circular No. 6 has a direct bearing on the same point. In a private communication Dr. J. B. Porter says:

> "I fully appreciate the fact that nearly everybody experienced in the storage of coal objects to the use of water for quenching fires in storage piles. I ex-

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* Univ. of Ill., Eng. Exp. Sta. Bull. No. 46.

press scepticism as to the harmfulness of water quenching. Recent information strengthens this scepticism, and I have come across several cases of successful fire fighting by the intelligent use of water. The fuel agent of the Canadian Pacific Railway states that he always recommends the use of water if the fire is a small one, and particularly if it is detected in an incipient stage. His practice is to locate the hot spot by driving test rods into the pile and then to dig a pit one or two feet deep right over the center of trouble; to drive and pull pointed rods or open pipes from it down into the heating mass and then to fill the pit with water, thus quenching the fire at the very center. At the same time if the fire is a large one he surrounds the whole heated part with a water curtain made by digging a ring ditch one or two feet deep and perforating its bottom with a row of holes as in ventilation. This ditch like the central hole is kept full of water from the hose, and if there is a tendency for the fire to be driven outward from the center, it is quenched by the water curtain.

''This method of putting out a fire is, of course, costly, but it is enormously quicker and less costly than that of digging out and results in far less loss of material. Personally, I am confident that it will prove successful in any ordinary case.''

Use of Carbon Dioxide and Bicarbonate of Soda

A number of attempts have been made to utilize the smothering effect of carbon dioxide gas and solutions of bicarbonate of soda in ways somewhat similar to those used in the ordinary hand grenade or fire extinguishers of the Babcock and of similar types. The effect of CO_2 on fire is certain if it can be localized and applied where needed. The difficulty in a large coal pile is to confine the gases. The evidence as to the effectiveness of these agents in fighting fires in coal piles is by no means conclusive either for or against the method.

Parr and Kressmann* have shown that the saturation of coal with a 3 per cent solution of bicarbonate of soda exerted very little, if any, retarding influence on the oxidation of the coal, although the saturation of the coal with a 10 per cent solution had quite a retarding influence. The experiments were carried on not for the purpose of finding methods which would extinguish a fire but which would prevent spontaneous combustion.

In a report upon the Thomas Automatic Fire Extinguishing System, which uses a solution of bicarbonate of soda, the Pittsburgh Testing Laboratory has reported as follows:

''In this method of fire extinguishing there are the following important factors:

---

* "The Spontaneous Combustion of Coal," Bull. No. 46, p. 45, Univ. of Ill., Eng Exp. Sta.

> 1. Quenching effect of water alone.
> 2. Smothering effect of carbon dioxide gas which is liberated at the surface of the burning material.
> 3. Smothering effect of the water vapor liberated by the chemical force.
> 4. Sealing and fire-proofing effect of the solid, non-volatile chemical.
> 5. Chilling effect caused by the heat absorption when the bicarbonate of soda is broken up by the heat.
>
> "We have examined carefully the photographs and data concerning fire tests made with large quantities of combustible materials in box-cars and open piles. We note that these tests bear out all that is to be expected; namely, that water charged with bicarbonate of soda and applied under high pressure extinguishes large fires almost immediately.
>
> "A saturated solution of bicarbonate of soda contains about 10 per cent or 13 ounces per gallon of water. Our practice has been to use from 2 to 4 ounces per gallon."

In response to Questionnaire *A*, the following information concerning the use of carbonated water was received from Robert Smith, Engineer of the Michigan Alkali Company, Wyandotte, Michigan:

> "The method used consisted of a tank in which the chemical was mixed and fed into the suction of a force pump which used the plant pressure of 65 pounds on the suction and boosted the same to 140 pounds. The nozzle was 10 feet long made of 1-inch pipe and it was forced into the pile, but I believe the best results were obtained by casting over the pile.
>
> "Our fire burned nearly two months, and towards the end seemed to increase. We used a solution of bicarbonate of soda and water and also turned over the pile and limited the pile to 25 feet."

In connection with the fire of the Cleveland, Cincinnati, Chicago, and St. Louis Railroad, bicarbonate of soda was used and J. L. Hampson, Fuel Inspector of the railroad says:

> "Water is mixed with soda in proper proportions by a patented apparatus, controlled by J. A. Thomas of Columbus, Ohio. It is necessary to first put out the fire on the surface of the pile, then with a ditcher, steam shovel, or clam-shell, to throw this coal over to a depth of 4 or 5 feet and then extinguish the fire thus uncovered. This is necessary for the reason that this chemicalized water will not penetrate more than 4 or 5 feet in some places.
>
> "We did not use the method until we had given up the idea of saving the coal remaining on the ground at Bellefontaine and cannot, therefore, say what might have been the result if we had tried it earlier, for I am inclined to think that we would have saved much more of the coal."

J. C. Dougherty, Coal Inspector for the New York Central Railroad, says:

> **"In one particular place where the pile was not over 10 feet in depth, a barrel of bicarbonate of soda was used. The entire barrel was scattered over a length not to exceed 30 feet. Water was turned in onto it and men drove bars into the coal and worked in the solution. Explosions were heard and several days later the fire was as bad as ever."**

Reports vary as to the effectiveness of the use of bicarbonate of soda in connection with fires on the Lake docks, and while it is undoubtedly true that if CO_2 can be confined, it will extinguish a fire, yet the advantage of carbonized water over plain water, in connection with the digging out of hot spots has not been thoroughly demonstrated.

Ventilation of Storage Piles

Of the forty-five fires reported in connection with Questionnaire *A*, six piles had some sort of ventilating device, three having vertical pipes, and in one case the method was not stated. Of the thirty-three piles in which no fires occurred one was ventilated by means of vertical boiler tubes.

In sixteen of three hundred and three storage piles reported on in answers to Questionnaire *B*, an attempt had been made to ventilate by means of iron or wooden pipes. In eleven of these sixteen piles fire occurred. These results do not suggest that ventilation as carried on is an efficient means of preventing spontaneous combustion and they agree very well with the results secured in the study of the fires in Chicago (see pages 73, 77).

The subject of the ventilation of coal piles is one upon which there is a great difference of opinion, and the evidence is very conflicting. It seems to be quite a common practice of Canadian railroads to ventilate their coal piles with a great deal of care, and it is the opinion of Professor J. B. Porter of McGill University and of S. H. Pudney, Fuel Inspector of the Canadian Pacific Railroad, that by means of proper ventilation spontaneous combustion can be prevented and the temperature of coal piles regulated to a very great extent. Other correspondents in Canada do not fully agree with this opinion. The experience of the railroads in the United States seems to differ widely upon this point, to judge from the replies to the questionnaires.

Attention should be called to the fact that many pipes placed in coal piles are intended merely for observing temperatures with no thought of ventilating the piles. Coal is a poor conductor of heat, and it is undoubtedly true that much of the so-called ventilation of coal piles has been inadequately done because only a few pipes have been placed irregularly throughout a pile. If ventilation is to be successful, it must be carefully done and pipes placed near together; but when so placed they interfere with rapid handling of the coal and increase the expense. The writers have not seen any of the Canadian coal piles that are reported to have been ventilated successfully, but a study of storage piles in the United States in connection with power plants has shown that the so-called ventilation is usually not well done and has been ineffective.

The Cleveland, Cincinnati, Chicago, and St. Louis Railroad, at its Mattoon, Illinois, storage yard found that large shaft-like openings in the coal pile were beneficial in lowering the temperature of the coal. These openings were dug with a steam shovel and were approximately 8 ft. by 8 ft. by 10 ft. deep.

At several Chicago storage piles it was noted that fires broke out near ventilation pipes, and at one place where the coal storage had been tiled horizontally with ordinary drain tile, the fire traveled along this tiling, which acted as a flue.

The subject is worthy of more careful study and possibly of experiment, but it should be remembered that climatic conditions may have an important influence on the success of any ventilation method and what is successful in the cooler, drier climate of Canada may not be successful in the much warmer and moister climate of Illinois. Moreover, in Illinois there is not the same drop in temperature at night as there is farther north, or at a higher elevation as, for instance, in Colorado or New Mexico. Consequently there is much less opportunity for a pile to cool off over night.

Mr. S. H. Pudney in an address* before the Canadian Railway Club of Montreal, gives the cost of ventilating coal as five cents per ton and states that in the case of Dominion coals, the holes are placed two feet apart, and in the case of United States coals three feet apart. In this same connection attention is called to the use of trenches dug through the coal pile at intervals. This practice is used by a number of railroads and has an effect similar to cutting a long pile up into a number of short ones by cross alley-ways.

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* Jour. of the Canadian Railway Club, Feb., 1919.

Summary of Methods of Fighting Fires

The methods of handling the fires as indicated by the questionnaires is shown in Table 11.

TABLE 11

METHODS OF FIGHTING FIRES

HOW HANDLED	Questionnaire *A*	Questionnaire *B*
Water only	5	11
Coal moved—no water	32	43
Coal moved and water used	7	19
Sodium carbonate solution	1	....
Not stated	....	2
Totals	45	75

25. *Damage to Property and Loss of Coal from Fires.*—In connection with the replies to Questionnaire *A*, it appeared that three out of forty-five fires involved a loss of property, but no statement as to the value was made. The following amounts of coal were reported lost as the result of such fires:

TABLE 12

LOSSES OF COAL DUE TO FIRES

COAL STORED	LOST
4700 tons	200 tons
800 "	75 "
35000 "	200 "
6000 "	10 "
8000 "	50 "

In connection with nine of the fires reported in the answers to Questionnaire *B*, there was damage to the adjacent property, but in eight of the nine reported cases the loss was less than $100.00, while in one case the loss was something over $1000.00.

The coal lost as the result of the fires was variously estimated at from less than one per cent to thirty per cent, but these figures are open to considerable question and at the best are only estimates. The average estimated loss by the fire varied from five to ten per cent of the coal in storage where the fires took place.

26. *A Study of Fires in Coal Piles in Chicago during* 1918.—An excellent opportunity to study fires in coal piles was offered in Chicago during the summer and fall of 1918. Probably no better time or place could have been chosen for such a study, because, during that time the Fuel Administration was urging consumers to store coal, and, owing to the great variety of the industries in the Chicago district and the large amounts of coal brought in for coke and gas making purposes, practically all kinds of coal were stored, in spite of the zoning system for the distribution of coal. It is impossible to state with any degree of accuracy the total amount stored, but practically every dwelling had some coal in its cellar, manufacturers were storing all they could, and the railroads and public service corporations were storing to the full capacity of their yards. The Commonwealth-Edison Company alone at its different plants in the city had about 500 000 tons. The fires studied therefore occurred with amounts of coal varying from that found in an ordinary house cellar up to piles containing thousands of tons.

The Commercial Testing and Engineering Company, 1785 Old Colony Building, of which Mr. Langtry is president, kindly placed its office at the disposal of the authors, and through the courtesy of J. C. Donnell, Chief of the Bureau of Fire Prevention and Public Safety, each morning a list of all the coal fires that had been reported the previous day was furnished. An attempt was made to visit all fires thus reported and to collect such information as would be of value in studying the problem. One hundred and twenty-one fires were visited and reported on, the Data Sheet (see Appendix I) being used to facilitate the gathering of uniform information. The fires visited have been classified under the following heads, depending on the cause of the fire:

Class 1. Fires due partially, if not wholly, to outside sources of heat.

Class 2. Combustion aided by foreign material in the coal.

Class. 3. Fires due to no apparent cause except the kind of coal or the method of piling.

Table 13 gives in tabular form a list of the fires studied, classified according to the place in which the coal was stored, and to the cause of the fire, with the approximate amount in storage in each case.

TABLE 13

CLASSIFICATION OF FIRES IN CHICAGO COAL PILES

PLACES WHERE COAL WAS STORED	Class I	Class II	Class III	Total	Range of Tonnage in Storage
Residences			1	1	10
Apartments and flats	9	2	16	27	20 to 500
Hotels, saloons, schools, churches, business buildings	3	4	12	19	40 to 8000
Fraternal homes	1			1	150
Manufacturing plants	2	13	18	33	30 to 50000
Coal yards		20	15	35	40 to 8000
Grain elevators			2	2	150 to 4400
Railway			1	1	12000
Public service corporations			1	1	10000
Totals	15	39	66	120	10 to 50000

A number of typical fires have been selected from those studied and detailed descriptions of these follow, arranged according to causes.

Class 1. Fires Due Partially, if not Wholly, to Outside Sources of Heat

In fifteen of the fires visited an outside source of heat seemed to be directly responsible for the spontaneous combustion of the coal. These sources of heat can be classified as follows:

Hot Water Tanks	1
Hot Pipes	6
Hot Furnace	4
Hot Chimney or Breeching	3
Hot Ashes	1
Total	15

The following is a summary of the information collected with reference to these fires.

Thirteen of the piles contained mine-run and two screenings. Thirteen were under cover and two in the open. None was ventilated. In four piles there was a segregation of the larger from the smaller sizes.

The length of time which elapsed between placing the coal in storage and the discovery of fire is shown graphically in Fig. 15, in which the number of fires is plotted against the length of time as given in the following tabulation:

Time in Storage	Number of Fires
3 weeks	1
8 weeks	3
12 weeks	6
15 weeks	1
16 weeks	1
No time stated	3

The peak of the graph is at twelve weeks; after that time the susceptibility of the coal to spontaneous combustion seemed to be less.

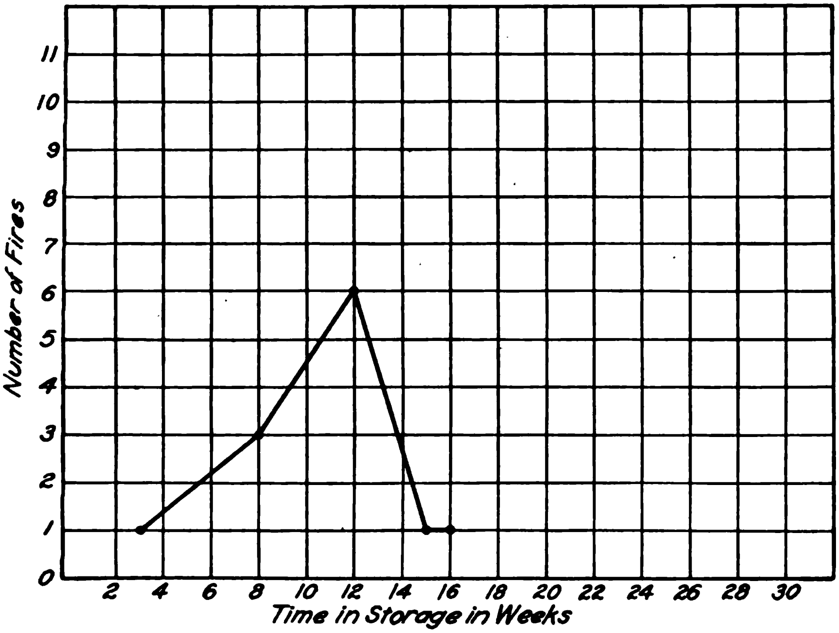


FIG. 15. GRAPH SHOWING LENGTH OF TIME COAL WAS IN STORAGE WHEN FIRE WAS DISCOVERED (CHICAGO COAL PILE FIRES, CLASS 1)

The cases hereafter discussed illustrate a too common practice that indicates ignorance or disregard of the fact that should be well known by all who attempt to store coal; i. e., that liability to spontaneous combustion increases very rapidly with increase in temperature, and therefore a coal pile should be kept away from all external sources of heat.

Because of the urgent necessity for laying in a larger amount of coal than in ordinary times, in many cases more coal was bought for storage purposes than could safely be stored in the usual space provided. Consequently any available space was used without regard to its adaptability and this fact explains some of the fires of this class. It is probable, too, that the proper method of storing coal had not been brought to the notice of all concerned.

A case where about seventy tons of Franklin County mine-run coal was stored in contact with a hot-water tank in the basement of a building is illustrated in Fig. 16. Heating of the coal started two or three weeks after the coal was placed in storage, and the center of the trouble was but a few feet from the tank. The janitor tried to keep the coal cool by wetting it with water two or three times per day, but finally called the fire department as the fire got beyond control. After the pile was flooded with water and the coal removed from around the hot-water tank, there was no more trouble.

Six fires were noted where the coal was stored in contact with or in close proximity to hot pipes. These storage piles ranged in size from forty tons to a few thousand tons and in all cases the coal was either mine-run or screenings.

A case where an uncovered sheet-iron smoke pipe leading from a furnace to the chimney was partially covered by coal is shown in Fig. 17. This pipe had several holes in it and at times became so hot that it could not be touched by the hand. After the fire, which resulted, was extinguished with water and the coal removed from the neighborhood of the hot pipe, there was no further trouble. Fig. 18 shows hot steam pipes placed in an uncovered trench about which coal was piled; fire resulted.

In four cases the heating was due to the coal being in contact with a hot furnace. All of these were in dwellings, and in every case the coal was mine-run. In two cases where the same kind of coal was stored in another part of the basement there was no trouble. Figs. 19 and 20 are views showing coal piled against furnace walls in basements. Fire occurred in both cases. Fig. 21 shows a chimney around which coal was piled; fire started in close proximity to the chimney. In another case a fire occurred in the basement of a flat in a coal pile at a point where hot ashes from the furnace had been piled against the coal.

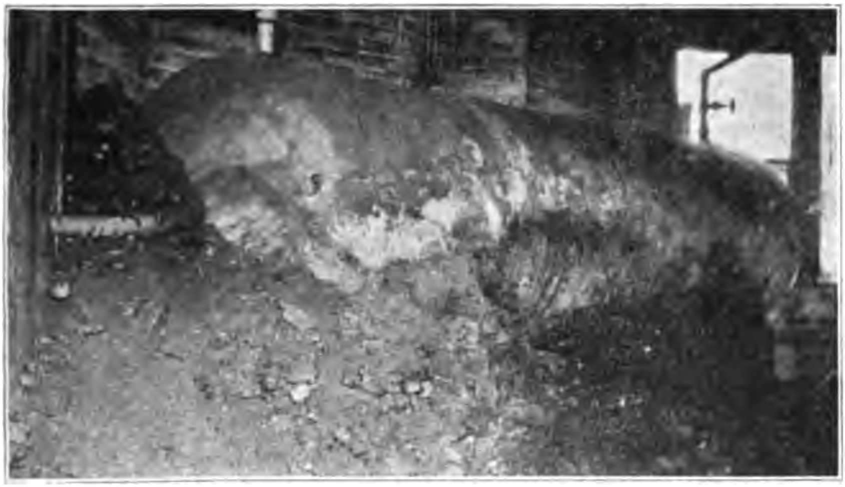


FIG. 16. COAL PILED AROUND HOT WATER TANK

FIG. 17. COAL PILED ABOUT SHEET IRON SMOKE PIPE

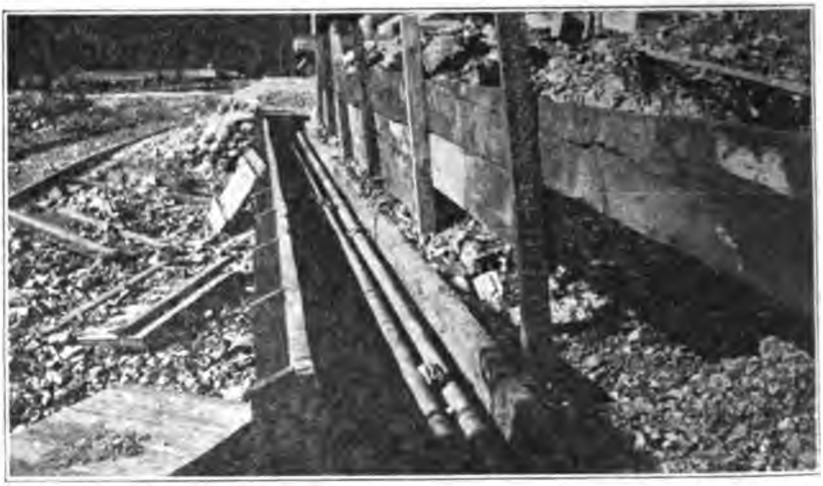


FIG. 18. HOT STEAM PIPES ABOUT WHICH COAL WAS PILED, CAUSING FIRE

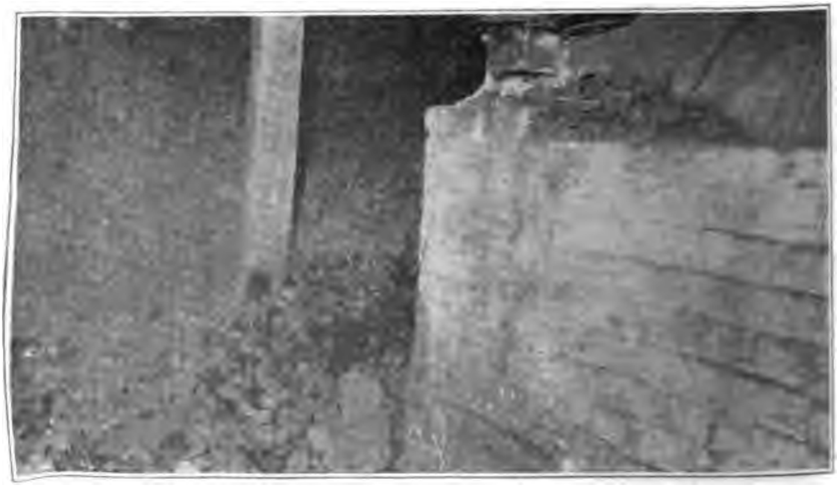


FIG. 19. COAL PILED IN CONTACT WITH BRICK WALL OF FURNACE (COAL HAS BEEN PARTIALLY REMOVED)

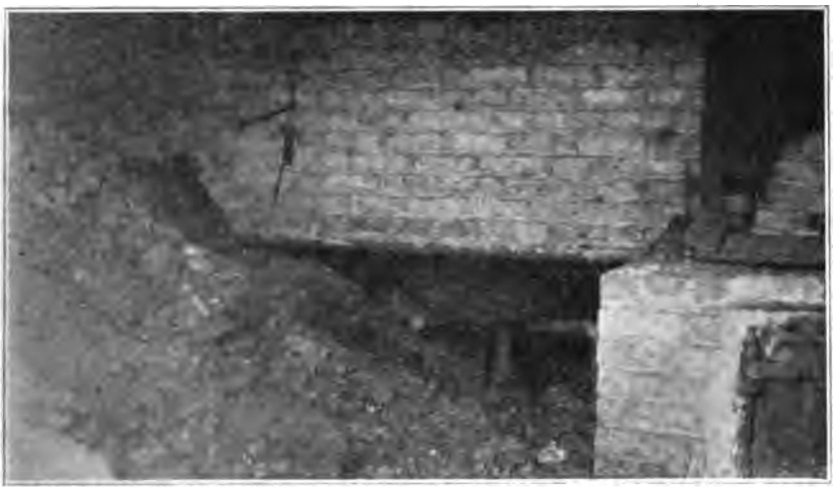


Fig. 20. Coal Piled in Contact with Brick Wall of Furnace (Coal Has Been Partially Removed)

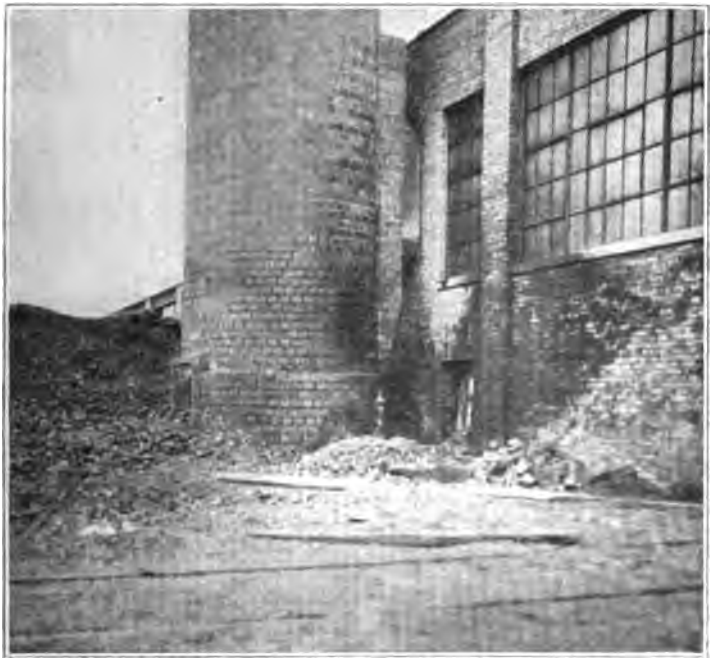


Fig. 21. Coal Piled around Base of Chimney (Coal Has Been Partially Removed)

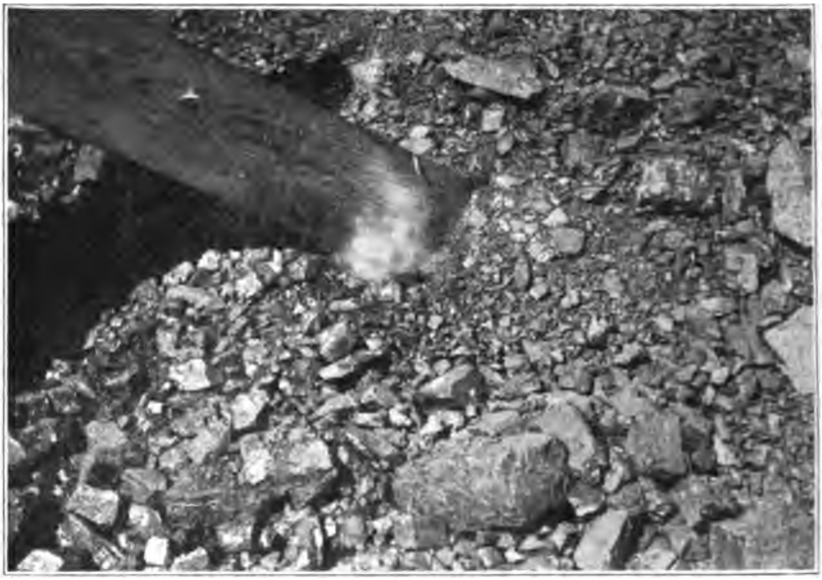


Fig. 23. Fire Starting in Coal Pile around Embedded Wooden Beam

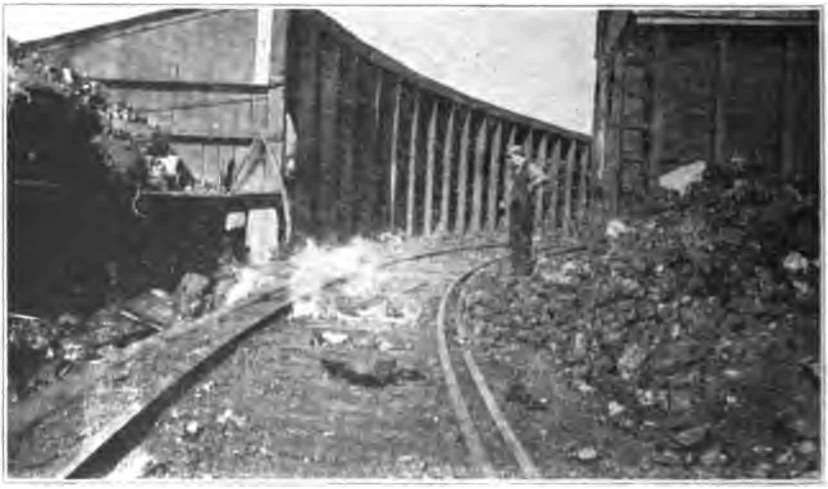


Fig. 24. Fire Starting in Coal Pile around Timbers of Trestle

Class 2. Combustion Aided by Foreign Material in the Coal

In thirty-nine of the fires visited the evidence indicated strongly that some foreign material such as wood, paper, rags, rosin, or sewer gas was responsible for starting the combustion as shown in Table 14.

TABLE 14

FIRES APPARENTLY DUE TO FOREIGN MATERIAL IN COAL PILES

FOREIGN MATERIAL	No.	Per Cent of Class II	Per Cent of Total Chicago Fires
Wood	31	79.5	25.8
Mixture wood, paper, rags, etc	5	12.8	4.1
Rosin	1	2.6	.8
Sewer gases	2	5.1	1.6
Totals	39	100.0	32.3

Additional information concerning these fires may be summarized as follows: Of the thirty-nine piles in question, eighteen were mine-run, sixteen were screenings, four were No. 5, and one was No. 3, No. 4, and No. 5 mixed. Thirteen of the piles were under cover and twenty-six in the open; two were ventilated and thirty-seven not; in twenty-seven there was a segregation of sizes, and in twelve no evidence of segregation.

Fig. 22 is a graph showing the relation between the number of fires and the length of time in storage for Class 2 corresponding to the following tabulation:

No. Weeks in Storage	No. of Fires
2	1
6	3
8	7
12	9
14	4
20	2
24	1
28	1
No time stated	11

As in Class 1, the most dangerous period was during the first twelve weeks.

In view of the fact that 25.8 per cent of the total number of fires visited in Chicago were apparently caused by wood being mixed

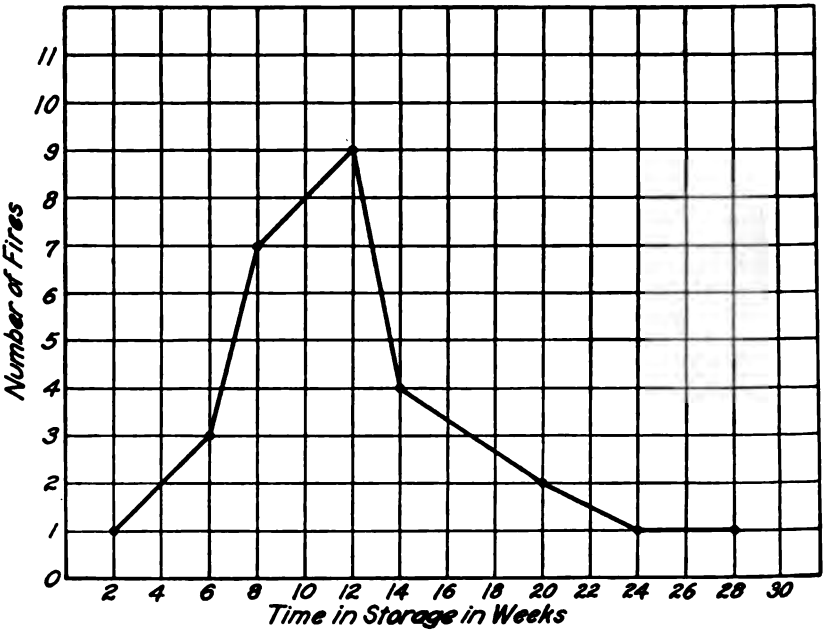


FIG. 22. GRAPH SHOWING LENGTH OF TIME COAL WAS IN STORAGE WHEN FIRE WAS DISCOVERED (CHICAGO COAL PILE FIRES, CLASS 2)

with or in contact with the coal, it is very important that those who store coal bear this in mind. Very often coal is stored around a wooden structure so that the wood is embedded in the coal. This is particularly the case where coal is placed in storage from a railroad track on a trestle.

There are two distinct ways in which such embedded wood may assist in starting combustion: first, by providing a flue along the timber for the circulation of an air current; second, by acting as a match in starting combustion at a lower temperature than that required for coal alone. It has not been definitely proved that wood acts in the latter way and the theory to that effect is by no means universally accepted as being true.

Figs. 23 to 30 illustrate cases where fires started alongside of or very near wood embedded in the coal piles in the form of supports to trestles or other structures, partition walls between piles, or enclosing walls for piles.

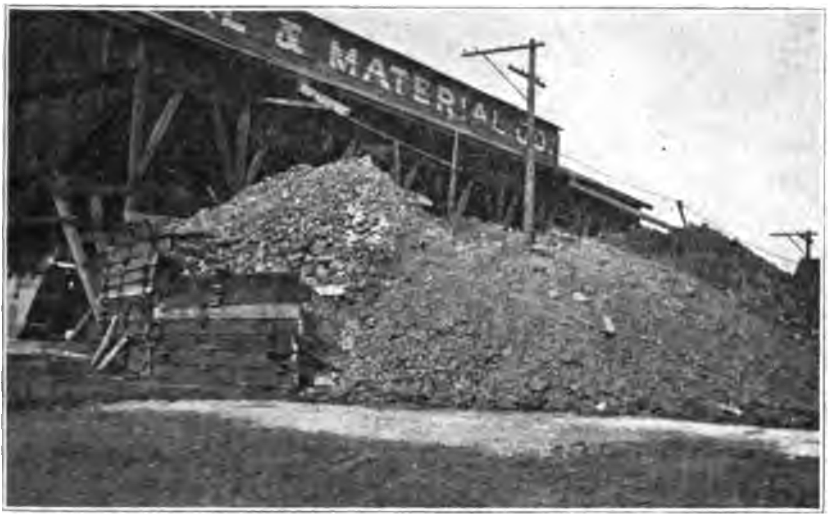


Fig. 25. View of Coal Pile Showing Timber Retaining Wall Anchored into Coal Pile by Wooden Supports

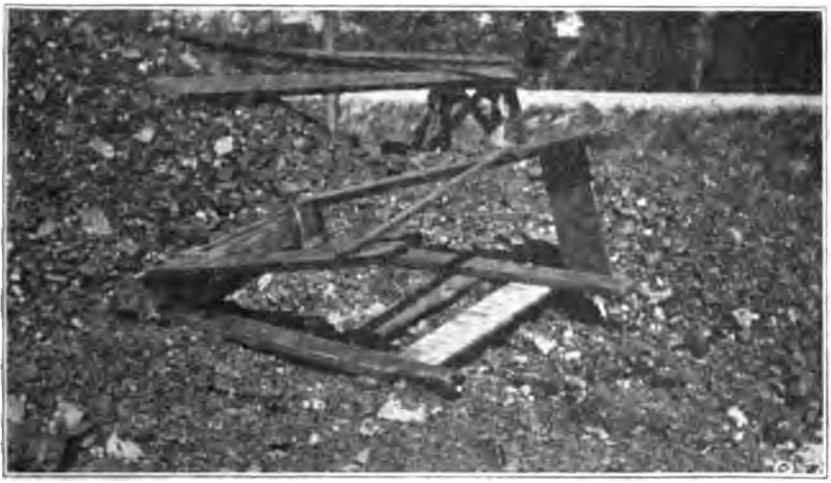


Fig. 26. Partially Burned Wooden Horse Removed from Coal Pile

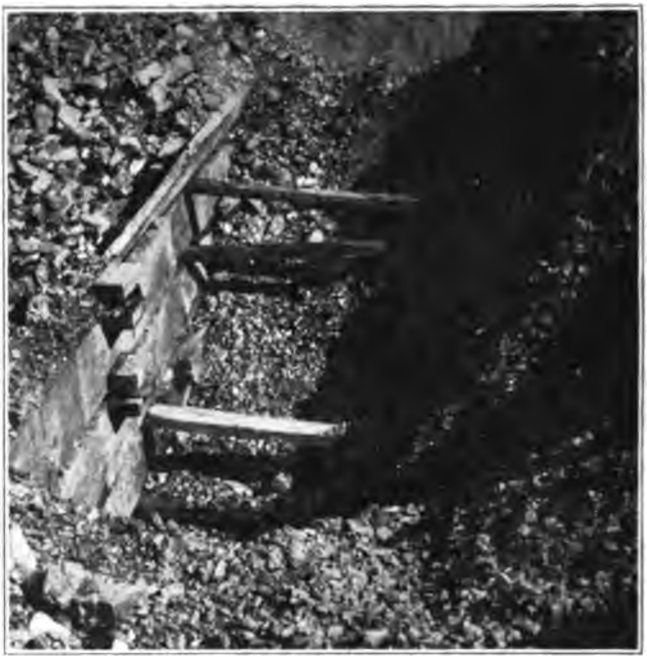


FIG. 27. BRACING TIMBERS EMBEDDED IN COAL PILE AROUND WHICH FIRE STARTED

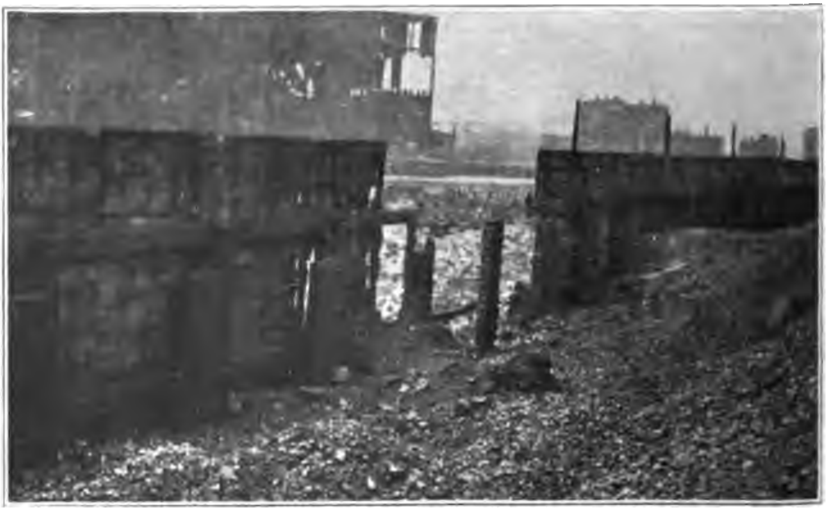


FIG. 28. WOODEN FENCE PARTIALLY DESTROYED BY FIRE IN COAL PILE, APPARENTLY DUE TO CONTACT OF COAL WITH TIMBERS OF FENCE

Fig. 23 shows a fire that was detected by smoke coming out along a beam embedded in the coal. Upon digging down into the pile the seat of the fire was found near the end of the beam. In a somewhat similar case fire started about an old coal retarder that had been surrounded by mine-run coal to a depth of twenty-five feet at the place where the fire occurred. Fig. 24 shows a very common condition. Smoke coming out along a track laid on top of a trestle indicates that a fire has started down in the pile. Such fires are usually found next to the leg of the trestle when the pile is dug into. In one case a fire was found at every leg of the trestle about which the coal had been dumped. Fig. 25 shows a common way of anchoring a timber retaining wall by means of timbers placed in the coal pile. Fire occurred in this pile but it was impossible to locate exactly the point of origin. A number of fires could be traced to no other cause than to similar wood anchors in the coal. Fig. 26 shows a wooden horse which formed part of a wheelbarrow runway that had been covered up with coal. Two of the legs are burned off at the end. Fig. 27 shows braces for a timber partition wall embedded in coal; a fire started around these braces. In another case a fire started about a plank carelessly left in a coal pile. Fig. 28 shows an enclosing wooden fence along which a fire started in a pile of Saline County screenings. A plank embedded in the pile, but projecting from it, thus furnishing a flue for air to enter the pile, was the apparent cause of fire in another case investigated. A pile of Pana No. 5 coal about some old partitions caught fire apparently near one of these partitions. In many coal yards the flooring under the coal piles is of wood and at a number of fires the origin was traced directly to this wooden floor. At other places where pieces of wood were embedded in the coal it was found when the coal was removed from the pile, that the hottest places were about these pieces of wood.

Fig. 29 shows a case where an attempt was made to ventilate a pile of screenings by placing horizontal wooden tubes about six inches square (indicated by arrows) in the pile as it was put in storage. A fire developed very close to one of these ventilating tubes. Fig. 30 shows an attempt to ventilate screenings by means of vertical wooden tubes (indicated by arrows). Fire developed very near these tubes.

Five of the fires visited were apparently caused by an accumulation of wood, paper, rags, etc, mixed in with the coal. At a service station visited, 180 tons of mine-run coal were placed in storage in the basement; spontaneous combustion occurred near the center of the pile and on removing the coal it was found that at this place there was a considerable amount of wood and rubbish mixed with the coal.

At a cold storage warehouse a fire developed in the storage pile at a point where there was a large amount of rubbish mixed with the coal (See Fig. 31). From this point the fire traveled toward a false bottom of wood which served as a flue.

A most interesting case of fire was noted at a yard where about 2500 tons of three-inch screenings from Murphysboro, Illinois, was placed in storage. Rosin had formerly been stored in this yard, and before it was used for coal storage a flooring of boards was laid on the ground over small quantities of accumulated waste rosin. The coal was piled on these boards, and within two months spontaneous combustion developed. When the coal was dug out with a crane, it was noticed that as the crane approached the bottom of the pile, the heat became more intense, and at the bottom there was a layer of coke about one foot thick on the boards which were burned to charcoal. A large quantity of molten rosin was mixed with the mass; the same condition was noticed at three different places in the pile. It is believed that the pressure and a slight heating of the coal caused the rosin to flow up through the space between the pine boards. Here it became mixed with the coal, and the kindling temperature of the mass was lowered to such an extent that it readily took fire. The kindling temperature of samples collected was so low that they could very easily be lighted by the flame from a match.

Two fires which occurred in basements of buildings started immediately over sewer outlets. There is no direct evidence that the gases from these sewer outlets caused the fires, but sewer gases are apt to be moist and hot and the proximity of the point where the fires started to the sewer outlets suggests that such gases raised the temperature sufficiently to cause, or at least materially to aid combustion.

One fire occurred in Chicago in clean sized No. 3 coal and the only explanation was that the coal had become heated by hot air entering the pile through a flue which led directly from the top of an adjoining boiler house.

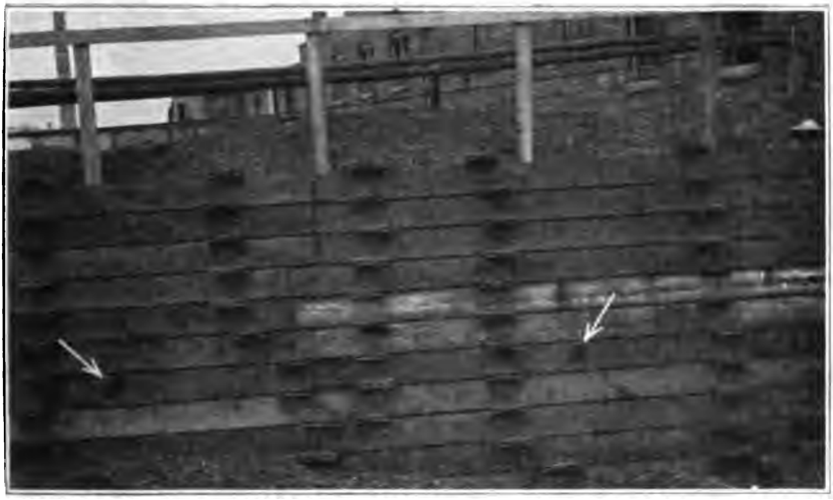


Fig. 29. View of Pile of Screenings with Horizontal Wooden Vents (Indicated by Arrows) near which Fire Developed

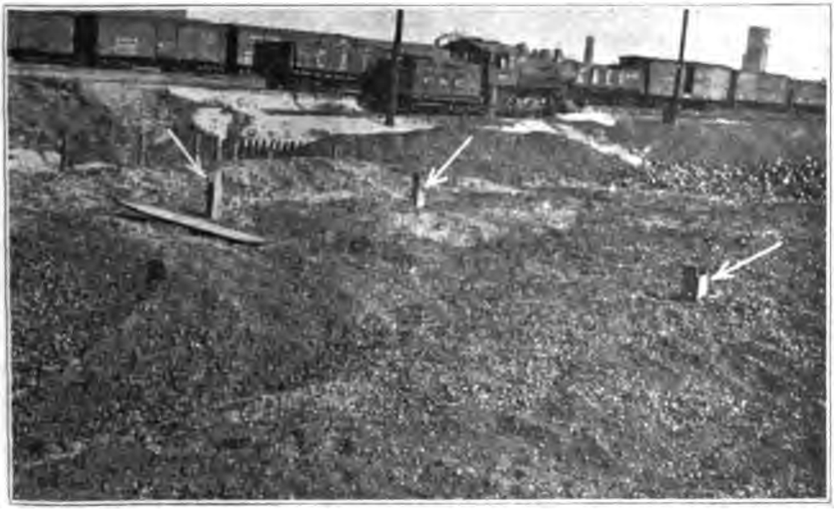


Fig. 30. View of Coal Pile, with Vertical Wooden Vents (Indicated by Arrows) near which Fire Developed

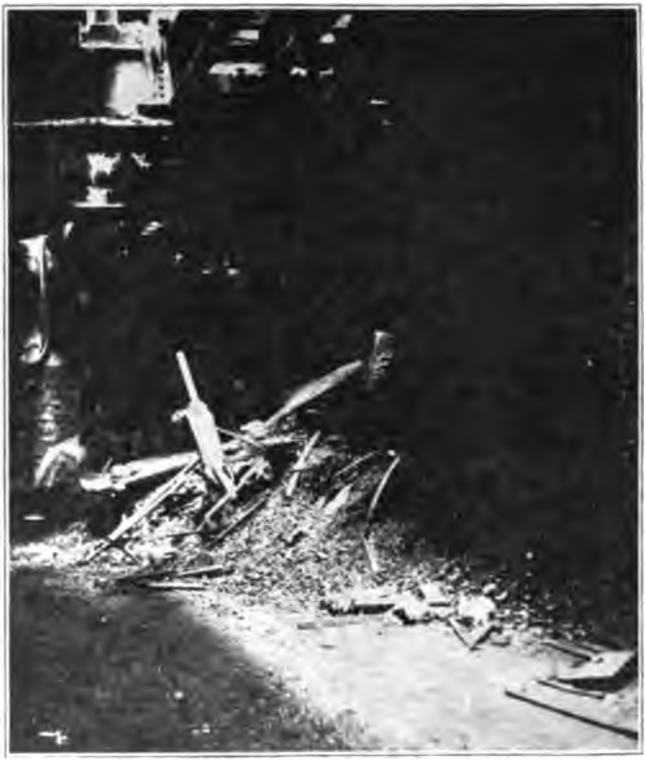


FIG. 31. WOOD AND RUBBISH IN COAL PILE AROUND WHICH FIRE STARTED

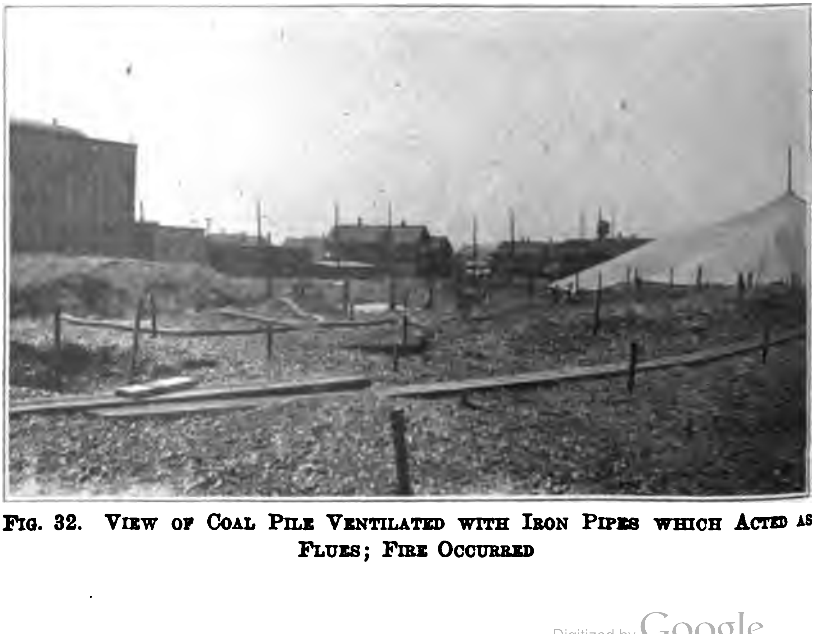


FIG. 32. VIEW OF COAL PILE VENTILATED WITH IRON PIPES WHICH ACTED AS FLUES; FIRE OCCURRED

Class 3. Fires Due to No Apparent Cause except the Kind of Coal, or the Method of Piling

In the case of sixty-six fires visited there was no apparent cause for the heating except in the kind of coal or in the method of piling. In a number of instances it was extremely difficult, if not impossible, to ascertain the exact conditions which caused the heating.

The most striking factor appeared to be the size of the coal stored. Eighty-six per cent of these fires occurred in mine-run or screenings, and in the case of those few fires which occurred in sized coal it was noted that there was a considerable amount of fine coal present, due to breakage in handling, weathering of coal, and improper screenings. The following table shows the number and percentage of fires occurring with each size of coal.

TABLE 15

RELATION BETWEEN SIZE OF COAL AND NUMBER OF FIRES

SIZE OF COAL	No. of Fires	Percentage
Mine run	35	53.0
Screenings and No. 5	22	33.3
Lump, 50 per cent, No. 5, 50 per cent	3	4.5
Nut	3	4.5
Lump	2	3.1
No. 4 Washed nut	1	1.6
Totals	66	100.00

Many believe that coal is safer if stored under cover, rather than in the open. A study of these Chicago fires would indicate that there is little difference whether the coal has a cover over it or not, for of the sixty-six fires in Class 3, thirty-four were under cover and thirty-two were stored in the open.

At four of the storage piles where fires were investigated an attempt had been made to ventilate the piles by using perforated iron tubes. Fires started very close to some of these tubes which apparently furnished the air needed for combustion. It was noticed that the smoke of a cigar was drawn down into one pipe which thus acted as an intake, while the smoke was blown outward at another pipe which served as a chimney; thus the pipes were producing a circulation of air through the pile.

Fig. 32 shows an attempt to ventilate with iron pipes, which was not effective, as fire resulted.

Special attention was paid to the results of segregation or *pyramiding* of the coal, as it is sometimes called, when unloaded into the storage piles. Coal will naturally segregate into different sizes if it is continually dumped on one spot as the pile is built up, the fine coal remaining at the center of the pile and the larger sizes rolling to the bottom; thus flues are formed that carry the air to the fine coal which oxidizes easily. This segregation of sizes was apparently the cause of many fires, as it was noted frequently that fires started near the place where coal was shoveled into a basement through a window. At this point there would be a natural segregation of sizes. The fire was usually found in the fine coal. Table 16 shows the importance of this item:

TABLE 16

RELATION BETWEEN SEGREGATION OF SIZES IN PILING AND NUMBER OF FIRES

	No. of Fires	Percentage
Sizes segregated	57	86.3
Piled uniformly	1	1.6
No information	8	12.1
Totals	66	100.00

The relation between time in storage and number of fires was as follows:

No. Weeks in Storage	No. of Fires
3	3
4	2
5	7
6	4
8	6
10	7
12	11
14	3
16	4
22	3
26	2
No time stated	14
Total	66

Fig. 33 is a graphical presentation of the information contained in the above table, and shows that as in the other classes of fires considered (see Figs. 15 and 22) the most dangerous period is during the first twelve weeks.

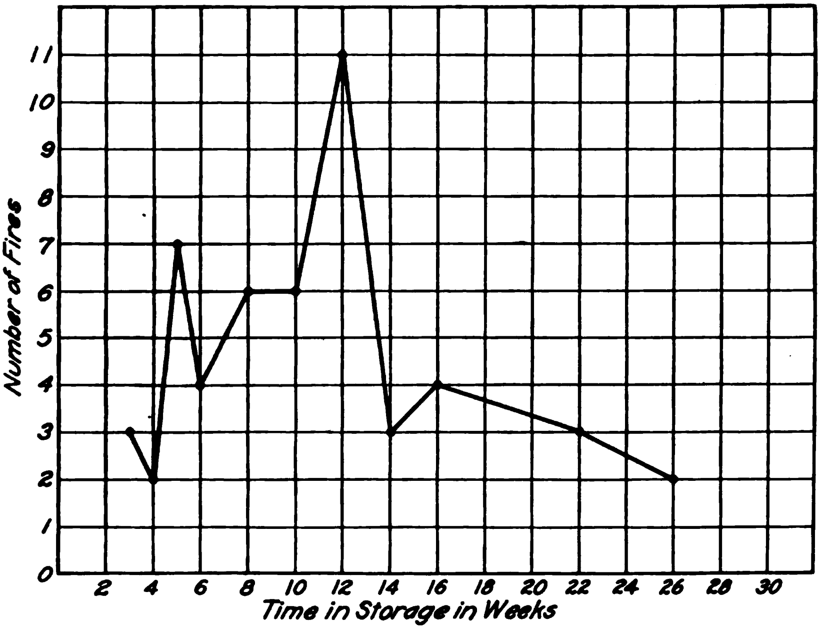


FIG. 33. GRAPH SHOWING LENGTH OF TIME COAL WAS IN STORAGE WHEN FIRE WAS DISCOVERED (CHICAGO COAL PILE FIRES, CLASS 3)

27. *Summary of Data from All Types of Chicago Fires.*—

Classification according to General Causes	No.	Per Cent
Class 1. Outside source of heat	15	12.5
Class 2. Foreign material in pile	39	32.5
Class 3. No apparent cause except kind of coal or method of piling	66	55.0
Total number of fires	120	100.0
Size of Coal		
Mine-run	66	55.0
Screenings	40	33.3
No. 5	4	3.4
No. 3, No. 4, and No. 5 mixed	1	.8
Lump 50 per cent, Screenings 50 per cent	3	2.5
Nut	3	2.5
Lump	2	1.7
No. 4 Washed Nut	1	.8
Total number of fires	120	100.0

Place of Storage	No.	Per Cent
Under cover	60	50.0
In the open	60	50.0
Total number of fires	120	100.0

Methods of Piling	No.	Per Cent
Sizes segregated	89	74.2
Piled uniformly	1	.8
No evidence of segregation	30	25.0
Total number of fires	120	100.0

The relation between length of time in storage and number of fires was as follows:

LENGTH OF TIME IN STORAGE (Weeks)	No. of Fires	No. of Fires (Cumulative Total)
2	1	1
3	4	5
4	2	7
5	7	14
6	7	21
8	16	37
10	7	44
12	26	70
14	7	77
16	6	83
20	2	85
22	3	88
24	1	89
26	2	91
28	1	92
No time stated	28	..
Total	120	

Fig. 34 shows graphically the relation between the length of time in storage and the number of fires occurring for all Chicago fires studied.

Fig. 35 is a cumulative curve which shows the total number of fires occurring plotted against the time in storage.

These data seem to show clearly that the following considerations should be taken into account in storing coal under the conditions prevailing in connection with the Chicago fires.

1. Coal should never be subjected to heat from outside sources, such as hot pipes, boilers, etc.
2. Foreign combustible material should be kept out of the pile.

3. The coal should be piled in uniform sizes and segregation prevented.
4. Sized coal only should be stored, if possible.
5. It is immaterial whether the storage is under cover or in the open.
6. The greatest liability to fires seems to be within the first three or four months and during that time special care should be taken to watch the pile for evidences of combustion.

The illustrations given are selected from a great number of photographs taken at more than one hundred fires visited in Chicago and in other cities, where the conditions were found to be similar in most respects to those found in Chicago with the exception that usually smaller amounts were stored.

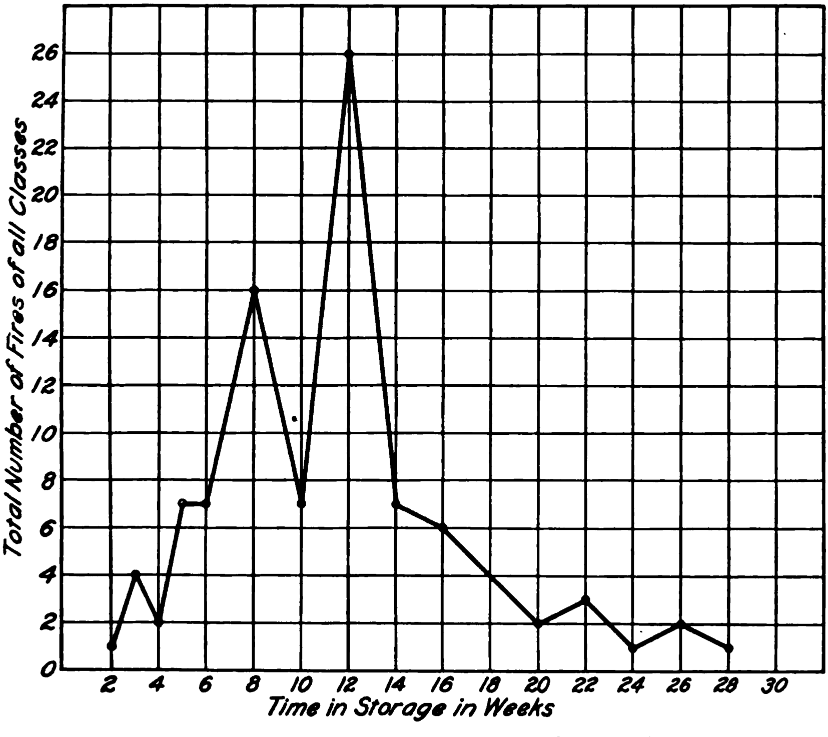


FIG. 34. GRAPH SHOWING LENGTH OF TIME COAL WAS IN STORAGE WHEN FIRE WAS DISCOVERED (ALL CLASSES OF CHICAGO COAL PILE FIRES)

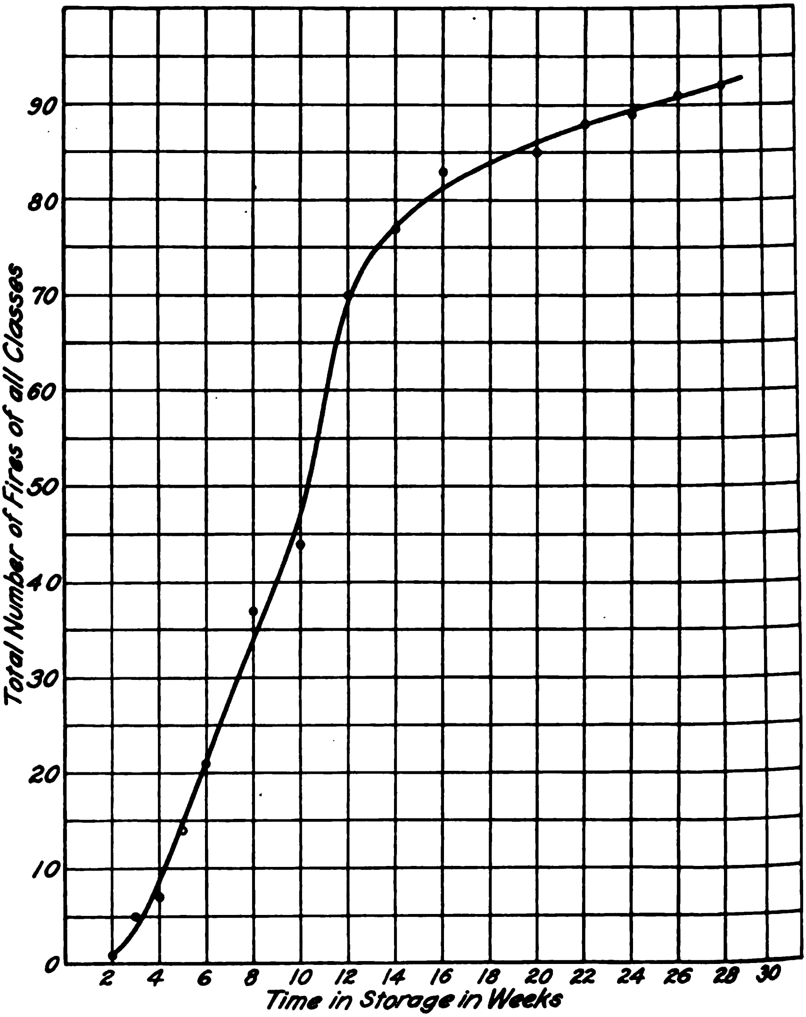


FIG. 35. GRAPH SHOWING RELATION BETWEEN LENGTH OF TIME IN STORAGE AND TOTAL NUMBER OF FIRES (ALL CLASSES OF CHICAGO COAL PILE FIRES)

IV. Effects of Storage upon the Properties of Coal

In Circular No. 6 the effects of storage upon the properties of coal were considered under the following heads:

1. Appearance.
2. Loss of heating value.
3. Firing qualities.
4. Spontaneous combustion.
5. Coking and gas-making properties.
6. Degradation or the increase in the amount of fine coal and dust due to breakage from handling and to slacking or weathering.
7. Loss in weight.

The conclusions in Circular No. 6 were as follows:

(a) The heating value of coal as expressed in B.t.u. is decreased very little by storage, but the opinion is widespread that storage coal burns less freely than fresh coal. Experiments indicate that much of this deficiency may be overcome by keeping a thinner bed on the grate and by regulating the draft.

(b) The coking properties of most coals seem to decrease as a result of storage, but coals vary greatly in this respect.

(c) The deterioration of coal stored under water is negligible, and such coal absorbs very little extra moisture. If only part of a coal pile is submerged, the part exposed to the air is still liable to spontaneous combustion.

Although a study of the data gathered in connection with railroad storage shows that a few consider that stored coal burns better than fresh and although similar opinions have also been given by those reporting on stationary power plants, yet the conclusion seems scarcely tenable. As pointed out by Parr in his bulletins, there may be a slight increase in B.t.u. value due to the washing out of the sulphur contents, thus giving a greater carbon content per ton in the resultant coal. This difference, however, is so slight as not to be appreciable in ordinary firing.

It should be remembered that very often the apparent deterioration in the coal taken out of storage is due not to any change in the coal but to the fact that the clam-shell or other device used for reclaiming, digs into the ground under the pile and mixes soil or refuse with the coal. It should also be remembered that the experiments at the University of Illinois, which indicated that storage coal can be burned as readily as fresh coal if a thinner bed is kept on the grate and if the draft is properly regulated, applied particularly to stationary plants and that the draft cannot be so well regulated in locomotive practice.

The following analyses furnished by W. D. Langtry confirm the conclusion that the decrease in heating value in B.t.u. of stored coal is very slight.

Coal stored by the Indianapolis Abattoir Company for two years showed a decrease in B.t.u. of only 5.85 per cent, as indicated by the following analyses:

	Coal Stored during 1918	Same Kind of Coal in Storage for Two Years
Moisture	13.66	17.19
Dry Ash	14.33	14.17
Dry B.t.u.	12 393	11 668

Indiana fourth vein coal showed a falling off of B.t.u. of only about one per cent, as indicated by the following analyses:

	Average of 472 cars Fuel Coal	Coal from Same Mine in Storage for one year
Moisture	13.66	17.96
Dry Ash	14.33	14.52
Dry B.t.u.	12 393	12 200

Variation in heating value in coal from Murphysboro, Illinois, was very slight after fifty-one days in storage, as is shown by the following figures, and the slight difference could be easily attributed to variation in sampling and analyses:

	About Dec. 1, 1918	Jan. 24, 1919
Moisture	10.08	10.65
Ash	15.41	14.90
Volatile	31.28	31.56
Fixed Carbon	43.23	43.89
B.t.u. (Moisture, ash, and sulphur free)	14 848	14 822

Another test of Murphysboro screenings placed in storage on the West Side in Chicago gave the following results:

	Coal from Boiler Room (or Fresh Coal)	Coal in Storage 4 Months	Coal in Storage 18 Months
	Per Cent Commercial	Per Cent Commercial	Per Cent Commercial
Moisture	10.25	12.44	11.89
Ash	9.08	9.16	7.98
Volatile	33.18	33.12	33.28
Fixed carbon	47.49	45.28	46.85
B.t.u. (moisture, ash, and sulphur free) .	14 816	14 761	14 713

The coal in storage 18 months was piled 10 or 12 feet high and the pile was about 150 feet long and 25 feet wide, bulkheaded with wooden anchors running into the pile. It was reported that the temperature was at no time more than a few degrees over 100 degrees Fahr.

The Engineering Supplement of the London Times for July 27, 1917, in discussing the storage of coal, says:

> "The loss due to weathering need not cause much concern since it would not be large from the pecuniary point of view. Colliery owners could in many cases select for storage the coals which, owing to their physical properties and chemical composition, are most immune from the effects of weathering or storage. Some tests on the effect of exposure on certain coals yielded the following results:

Description of Coal	Storage Condition	Effect on Calorific Power
Bengal coal, India	Large stocks exposed for 12 months in the open	Depth of stock 4 ft., aver. loss 7.6 per cent
Scotch anthracite cobbles*	Samples exposed to all weathers in England for 2¼ years	Loss 3.3 per cent
Scotch house coal*	Sample exposed as above for 2¼ years	Loss 8.4 per cent

* These coals, if stored in large quantities, would not show such a loss, as the total coal which is covered by the overlying layers would be protected from the effects of the weather."

V. STORAGE SYSTEMS

In Circular No. 6, Chapter V, the points to be considered in choosing a storage system and the requirements of an ideal storage plant were discussed. The following types of storage were described in considerable detail:

Hand-operated storage systems.
Storage by motor truck.
Pile storage from cars without a trestle.
Trestle storage.
Storage with side dump cars.
Side-hill storage.
Use of mast and gaff arrangement in storage.
Locomotive crane storage.
Parallel track storage.
The trestle and crane system.
Circular storage.
Steeple towers.
The Hunt system.
Bridge storage.
Deep reinforced concrete storage bins.
Underwater storage.

Since the publication of Circular No. 6, a large number of storage plants have been investigated and the following descriptions include a number of new systems and also additional information about some types that were described in Circular No. 6.

28. *Hand and Truck Storage.*—There are no developments to report in connection with hand storage systems since the publication of Circular No. 6.

The pile of coal stored by motor truck at the University of Illinois, as described in Circular No. 6, is still in storage and there have been no evidences of fire. The coal was screened 1½ nut in size when stored during 1918 and though the outside of the pile is now finely pulverized, the coal exposed by digging into the pile to the depth of a foot has the same appearance as when stored.

29. *Pile Storage.*—Pile storage from cars which run on a track laid on the coal pile and raised from time to time is probably the method most widely used by railroads. It is also adopted to some extent by commercial plants because it is the easiest in application, and requires only a small expenditure of money for permanent equipment and because the track can be moved from place to place as desired.

The objections to the method are:

> (a) The pyramiding effect; that is, the segregation of fine coal at the center and top of the pile is intensified as the locomotive and loaded train crush the coal under the track.
>
> (b) It is not practicable to divide the coal by cross-passageways so as to make a number of small piles and thus render each pile easy of access for reclaiming.
>
> (c) When coal is piled in this way adequate track provision for moving the coal quickly is apt to be neglected until it is time to move the coal and a track cannot then be put in place quickly enough to save the pile. Where this method is used the track should be moved from the top of the pile to the surface alongside the pile so as to provide for the rapid loading out of the coal, if necessary. The use of a standard railroad ballast spreader to spread the coal on the pile is to be preferred to the ordinary method of dragging a tie through the coal.

Mr. J. F. Hanson, Fuel Supervisor of the Cleveland, Cincinnati, Chicago, and St. Louis Railroad, says:

> "Our experience this year (1918) has certainly demonstrated that coal cannot be stored successfully by dumping cars over the track and then raising the track through the coal."

On the other hand during 1917 the Illinois Central Railroad successfully stored run-of-mine in this way at two mines near Duquoin, Illinois. Although the method has been successfully used in a number of instances, it is the least desirable of all methods and is to be avoided if possible.

Pile storage with the tracks placed alongside of the pile rather than on top is extensively used, and has not the same disadvantages as pile storage with the tracks raised on top of the pile. Fig. 36, shows long piles of the Missouri, Kansas, and Texas Railroad, Enid, Oklahoma.

The track should be kept in place, so that the coal can be loaded out promptly, if necessary, and should not be moved as soon as the coal has been stored, as is sometimes done. Two tracks between piles give greater flexibility in switching cars than one, though, if necessary, one track will suffice as the locomotive crane can be used for switching the cars. When two tracks are used the crane runs on the track next the pile and unloads from cars on the parallel track. The height of such piles should preferably be limited to 16 to 20 feet and, to prevent pyramiding and breakage, the coal should be laid down in layers as thin as practicable, usually not over three feet thick and spread over the full width and length of the pile. It should not be piled up to the full height at one spot in the pile. The clam-shell bucket should also preferably be lowered to a point just above the surface of the pile before being dumped so as to minimize breakage.

Fig. 37 shows the standard system of the Missouri Pacific Railroad. For coals that are liable to spontaneous combustion, the alleyways across the piles are used; otherwise the piles are continuous.

Locomotive cranes or ditcher appliances (see Figs. 38 and 39) afford great flexibility in placing coal in storage and in reclaiming it; they utilize equipment with which railroads and many industrial plants are usually already supplied. Piles can be made of any length that the available space permits and the width is limited only by the reach of the crane. They are also particularly well adapted for storing coal in circular piles.

With respect to usefulness for reclaiming, there is probably little difference between a revolving shovel and a locomotive crane or ditcher, but a shovel cannot be used for unloading from the cars. Any equipment of this kind requires a permanent investment in track for which, however, a rental may be charged to the storage account.

30. *Trestle Storage.*—Trestle storage requires an initial permanent investment in a structure which is used for only a short time. The legs of a trestle embedded in a coal pile are apt to be starting points for fires. In dumping from a trestle it is impossible to avoid pyramiding and the breakage is often excessive. The bents of a trestle interfere with the loading out of the coal and cleaning out of the bin. The combination of a trestle for unloading and a crane for reloading is satisfactorily used.

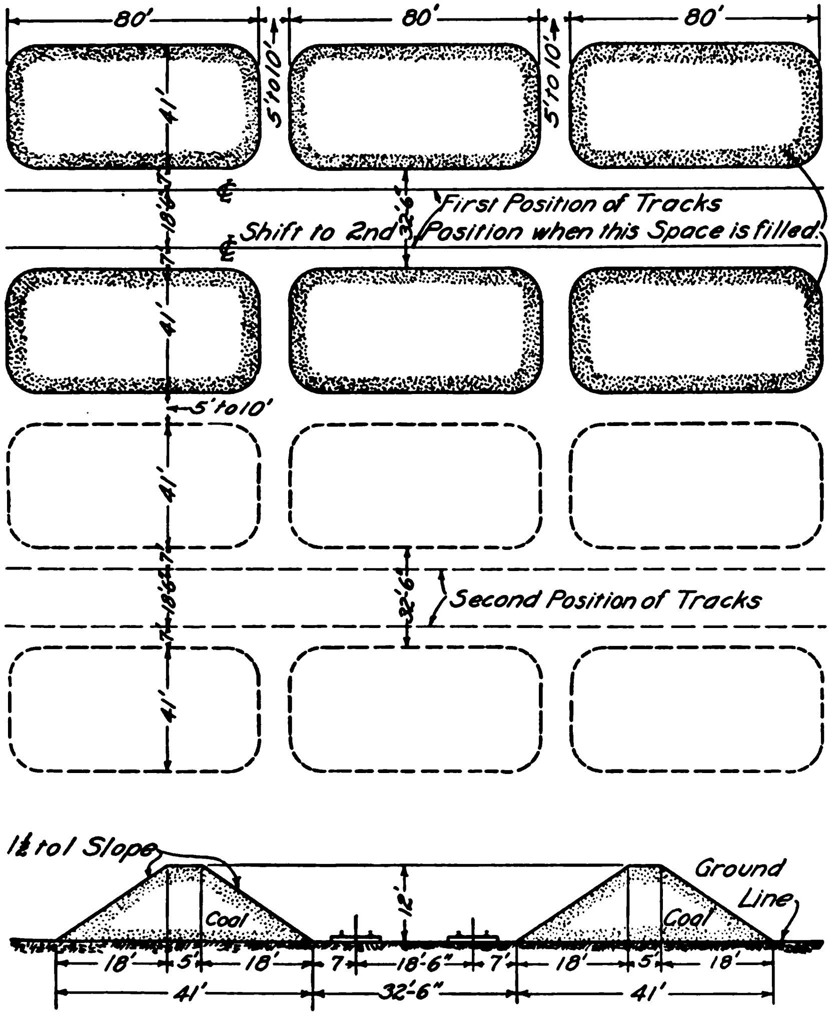


FIG. 37. PLAN AND SECTION ILLUSTRATING STANDARD COAL STORAGE SYSTEM OF MISSOURI PACIFIC RAILROAD

An innovation in storage trestles is claimed by the Seaboard Air Line Railroad in connection with its trestle storage at Jackson and Savannah, Georgia. Trestles are constructed as shown in Fig. 40 and the ground is covered with plank. The *A* section extends the entire length of the pile and is made air-tight, except at the ends. The pur-

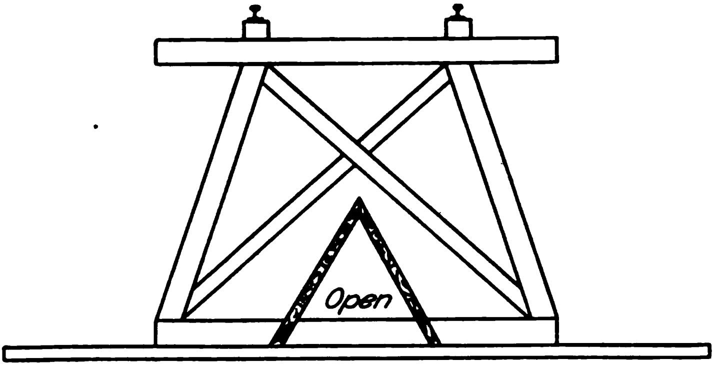
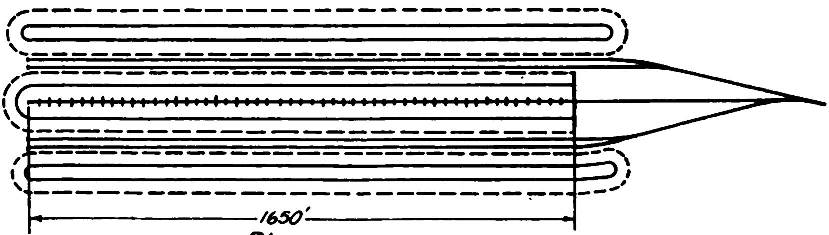


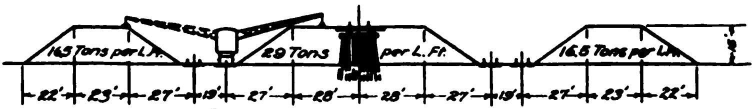
FIG. 40. COOLING DUCT UNDER PILE

pose of this flue is two-fold: to help in shifting the coal from under the trestle and thus facilitate loading by crane, and also to act as a cooling agent by conveying cool air the entire length of the trestle without having it come in direct contact with the coal. Run-of-mine coal containing a large amount of slack was stored. An effort was made to store low sulphur coals, because the action of water on sulphur in coal forms sulphuric acid, which breaks up the lumps into slack. At no time was a temperature above 70 degrees noted in pipes placed in the piles.

Fig. 41 shows the Standard Storage System adopted by the New



Plan



Typical Cross Section

FIG. 41. PLAN AND SECTION ILLUSTRATING STANDARD COAL STORAGE SYSTEM OF THE NEW YORK, NEW HAVEN, AND HARTFORD RAILROAD (TONNAGE GIVEN PER LINEAR FOOT)

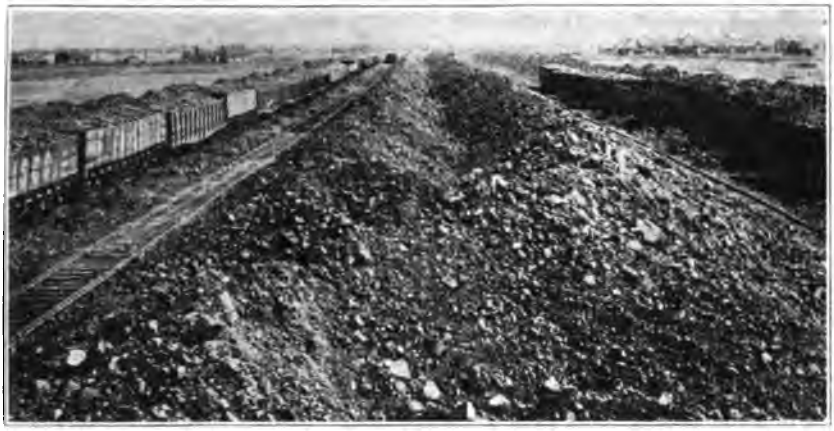


FIG. 36. RAILROAD COAL STORAGE PILE AT ENID, OKLAHOMA

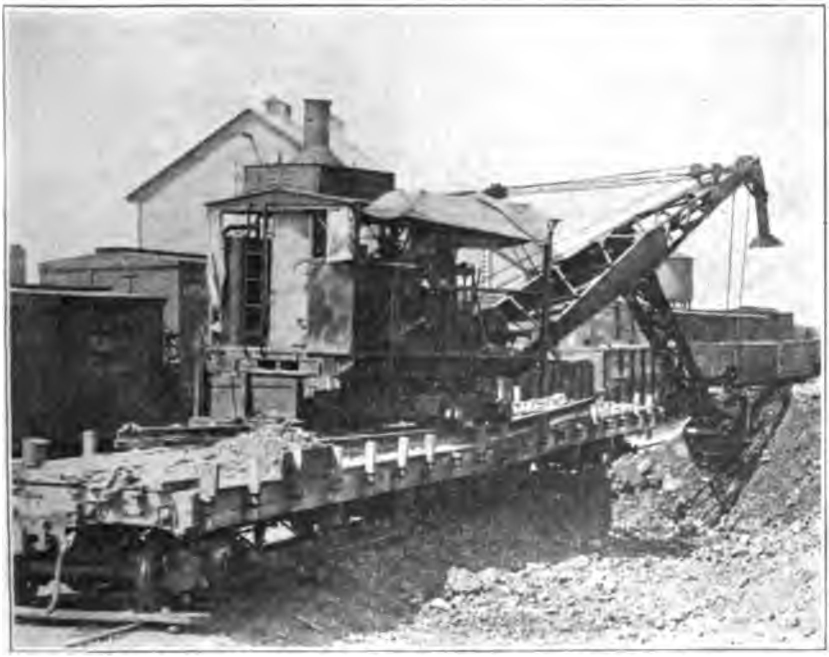


FIG. 38. DITCHER RECLAIMING COAL

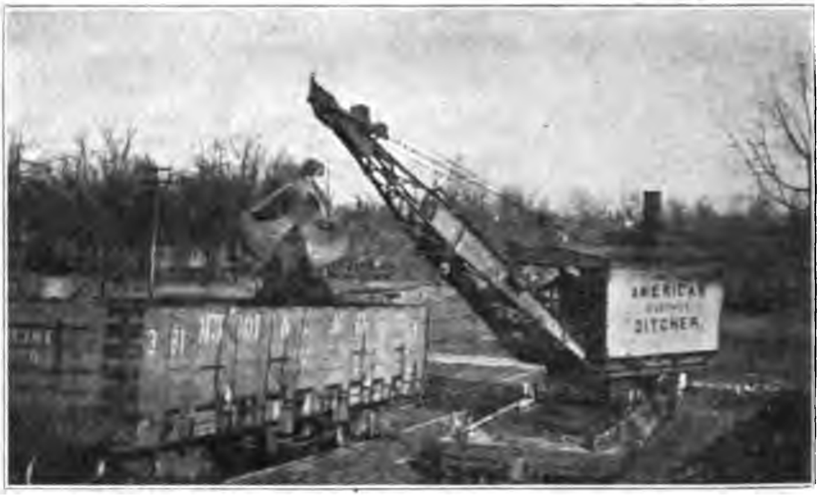


Fig. 39. Ditcher Reclaiming Coal

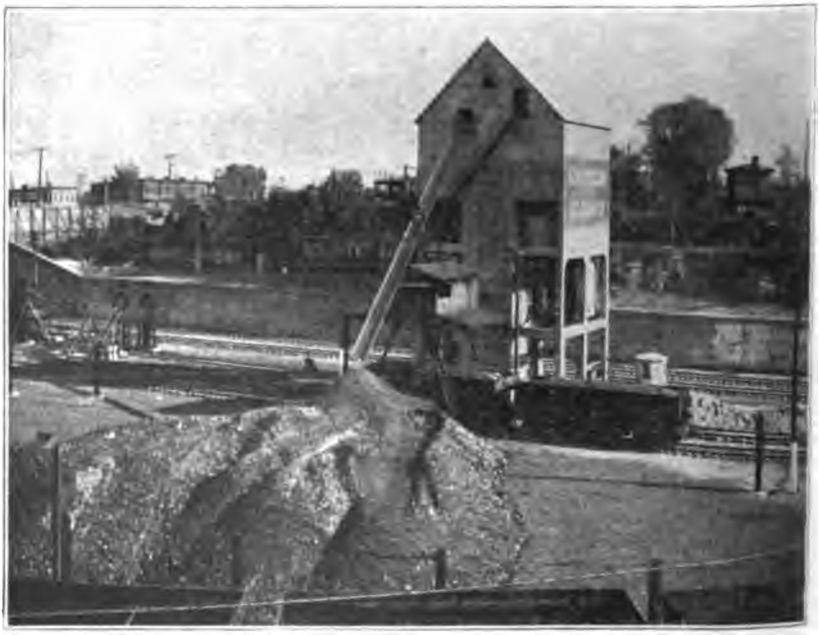


Fig. 42. Drag-Line Coal Storage and Coal Handling Plant of Southern Railway at Air Line Junction, Virginia

York, New Haven, and Hartford Railroad at three coal storage yards recently installed. A trestle 1600 to 1700 feet long and 16 to 17 feet high runs through the center of each yard and on either side is a pair of parallel tracks. The trestle supports are wooden piling and the tracks on top of the trestle rest on steel girders. The two pairs of parallel tracks approach at the yard entrance. On one of the parallel tracks on either side of the center trestle a locomotive crane operates with a swinging boom which transfers the coal dumped from hopper bottom cars running on top of the trestle to piles built up about the trestle and also outside of the parallel tracks. The average height of the coal pile is 20 feet. The coal is trenched to a depth of 8 to 10 feet regularly throughout the pile and in addition ventilation pipes are put down to the bottom of the pile 40 to 50 feet apart. Temperature tubes are inserted in these pipes and readings are taken regularly for indications of heating.

Side hill storage is applicable only in certain districts and with it the pyramiding effect is exaggerated.

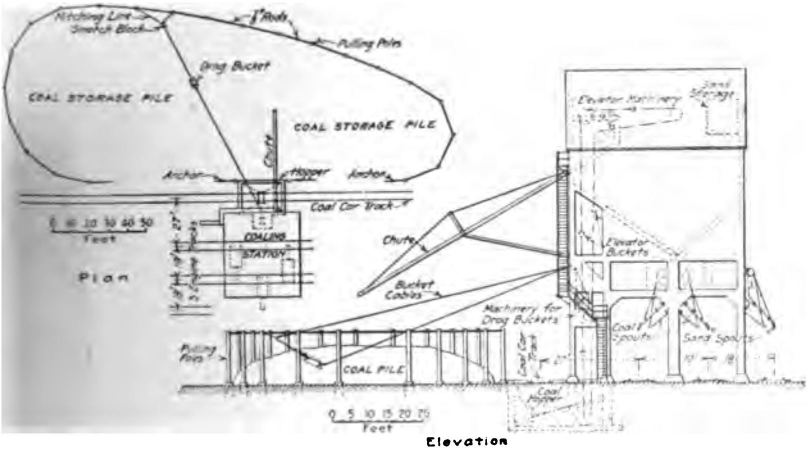


FIG. 43. PLAN AND SECTION OF COAL STORAGE AND COAL HANDLING PLANT OF SOUTHERN RAILWAY AT AIR LINE JUNCTION, VIRGINIA

31. *Drag-Line Bucket Storage.*—Figs. 42 and 43 show in perspective, in plan, and in section the drag-line type of storage used by the Southern Railway. The storage piles contain from 3000 to 10 000 tons each, with a depth of not more than 10 feet. The railway cars

dump the coal into a track hopper, from which it is fed by a loading device to a bucket elevator. This delivers it either to the storage bin of the coaling station or to a gravity chute which discharges at about the center of the storage pile and from this point it is distributed over the area of the pile by the drag scraper.

This scraper also returns coal from the storage pile to the track hopper and elevator for the supply of the locomotive coaling bin. The storage pile is of irregular form and is surrounded by poles, placed about 20 feet apart, to which is attached the cable line for operating the bucket. It has been found that the best height for these piles is about 12 feet. They are made of steel H-beams, each set in a concrete base and are connected at the top by a row of 7/8-inch rods.

The scraper bucket is operated by means of a double drum friction hoist driven by a 25 hp. motor geared directly to a countershaft. With this equipment the operator can take the coal delivered from the chute and distribute it between this point and the post to which the snatch-block is attached. To reach the space between two posts, lines may be fastened to them and the snatch-block attached to the lines. By shifting the block from pole to pole any point within the coal storage area can be reached. When it is necessary to supply the bin of the coaling station, the position of the bucket or scoop is reversed, its open end being turned toward the coaling station, the backhaul cable then becoming the hauling line.

Drag-line storage systems are somewhat less flexible than the locomotive crane type but they require less initial investment, for the motor, ropes, bucket, and posts are probably less costly than a crane, and no track investment is required.

32. *Silo Type of Storage Pockets.*—The silo type of coal storage pocket has been used by a number of industrial plants for strictly storage purposes and by retail dealers and railroads for temporary storage and current supply. The silos are constructed of reinforced concrete, of steel plates, or of wooden staves and are often built in batteries of two or more with a capacity of 100 to 1000 tons. They vary in diameter from 14 to 30 feet and in height from 24 to 75 feet. Old steel tanks have been remodeled in some cases to serve as coal pockets. The silos are filled from hopper bottom cars which are un-

loaded through a track grating into the boot of an elevator which delivers the coal at the top into a conveyor line running over the top of the silos and arranged for automatic dumping into any desired silo. Silos are usually set high enough above the ground so that the coal can be loaded out by gravity through chutes either into a conveyor for transferring the coal to a power plant, or into wagons; a screening arrangement may be located at the discharge point. At the top of the silo, in order to prevent breakage, the coal may be dumped upon a zig-zag coal ladder consisting of a series of projections from the walls of the silo, the coal falling from one to the other so as to decrease the height of drop.

The advantages of the silo are: small ground space required, less labor required for loading and unloading, and the ease with which the coal can be transferred by means of elevators and conveyors from one silo to another in case of a rise in temperature.

The disadvantages are: high initial cost of installation and excessive breakage when the coal is dropped through any great height, and the necessity of moving the entire contents of the silo below the heating spot if heating occurs.

It is believed by some that the danger of the coal heating is reduced to a certain extent because every load that is taken out of the silo shifts the position of the remaining coal. Such movement of the coal may also act injuriously by causing the circulation of air in an insufficient quantity. If heating occurs, the bin may be flooded with water, provided it has been constructed to withstand the pressure of the coal with the interstices filled with water.

Fig. 44 illustrates a coal pocket of wooden stave construction, which consists of a battery of four silos 34 feet high, three of them being 20 feet in diameter and the fourth one only 16 feet in diameter. The storage capacity of the plant is about 1500 tons of anthracite.

The coal is dumped from the car into a steel-lined concrete hopper from which it slides into a steel boot. It is then elevated by continuous buckets to a point over the bins, from which it is distributed as desired through several chutes and valves. To avoid excessive breakage it is lowered to the level of the coal in the different bins by a zig-zag coal ladder. The power is furnished by a 10 hp. electric motor.

The cost of operating this plant is given by the H. M. Tuttle Company of Bennington, Vermont, as follows:

Plant Expenses for One Month

1.	Depreciation	$31.59
2.	Real Estate Expense	
	Tax apportionment	14.08
	Insurance	10.33
	Land and track rental	22.01
3.	Light and Power	8.70
4.	Degradation	
	Shortage in weight of cars and loss from screenings for 1259.04 net tons at $.39 per ton	491.09
5.	Wages	
	Unloading and yard employees	202.46
	Total	$780.26

Thus, since 1259.04 tons were handled during the month, the cost per net ton would be $0.62. The average cost per net ton for nine months was $0.554.

The cost of silos similar to those shown in Fig. 44 was given in February, 1919, as $2.20 for a 400-ton bin to $2.60 for a 200-ton bin per ton of coal capacity for the materials on board cars at Rutland, Vermont, at the plant of the Creamery Package Manufacturing Company, builders of such silos. Erection and freight are said to add not over fifty cents per ton.

Fig. 45 shows a stave silo plant elevated for bottom discharge to retail trucks.

Concrete or steel construction for silos has an advantage over wood construction as the repair bill is less, and the fire risk is greatly reduced. With reference to a concrete storage pocket, F. W. Stock & Sons,* Hillsdale, Michigan, under date of January 30, 1919, says:

> "The coal storage tanks erected about a year ago have proved a very successful investment for us as a manufacturing concern. To prevent spontaneous combustion the coal should be drawn in rotation from all the tanks and not from only one; otherwise, there is considerable chance of spontaneous combustion, particularly if the coal happened to be slightly damp when put into the tanks."

The Macdonald Engineering Company, Chicago, Illinois, builders of this plant, reports upon these silos after they have been operated two years, as follows:

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* Illustrated and described in Univ. of Ill., Eng. Exp. Sta. Circular No. 6, p. 95.

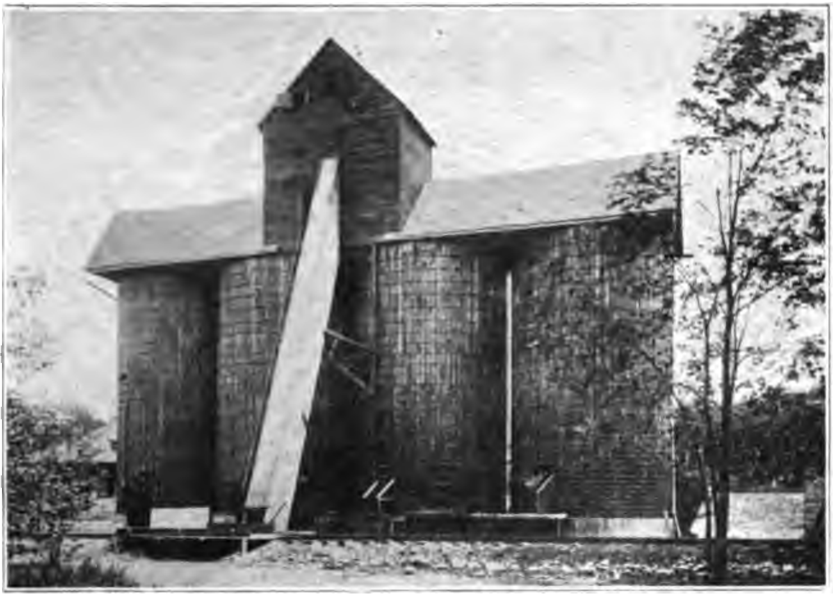

Fig. 44. Wooden Stave Silo Coal Storage Plant

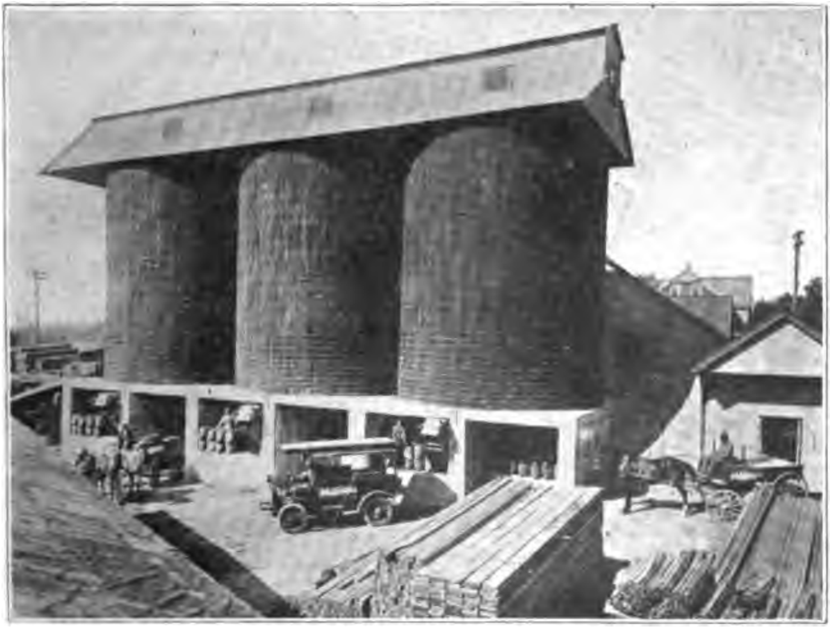

Fig. 45. Wooden Stave Silo Coal Storage Plant, Arranged for Bottom Discharge

> "One of the bins in this plant which is 28 feet in diameter and 70 feet deep was kept continuously filled with coal from sometime in October, 1917, to August, 1918. The contents in this time had not been disturbed to amount to anything. No perceptible rise of temperature was observed until sometime in August, 1918, when the moisture originally in the coal seemed to be pretty well evaporated and the temperature began to rise. We had equipped these bins with a means for flooding them with water. About the first of September when the temperature was at the ignition point we tried an experiment and turned on the water. This resulted in so much steam and gas that it was discontinued, as our man feared it might produce an explosion. Immediately after shutting off the water we drew out 10 tons of the hot coal through the bottom discharge spouts of the bin. This coal was smouldering and the amount drawn seemed to include all that was on fire. We then closed the valves and sealed them air-tight with a putty of clay. Two or three days later an inspection showed that the trouble was over and the temperature nearly normal, since which time there has been no further increase in temperature. At the date of the heating we had 65 feet of coal in the bin and we found that the fire was located on the hopper bottom of the bin and occupied the space between the outlet openings and the manhole which was built in the vertical outside wall of the bin. The indications were that there had been just enough air ventilation between the outlets and this valve to furnish the required amount of oxygen for combustion. From this experiment it would seem that if the opening were sealed perfectly air-tight there would be no rise in temperature. After using this plan for two years the only suggestion that the owners had to make is that they would use smaller bins for any future storage, so that if they had to change the coal from one to another there would not be so much to handle."

W. A. Joshel, wholesale and retail coal dealer of Geneva, Illinois, has two silos 60 feet in height and 18 feet in diameter. One of these is partitioned into four bins and the other into two bins by means of 2x4's laid flat. The silo walls are 6-inch reinforced concrete. There has been no trouble from heating; the coal is kept in motion by being constantly drawn out at the bottom. The breakage has been heavy and Mr. Joshel advises building silos much lower and either building more of them or increasing the diameter. He is able to unload a 42-ton car of anthracite, range size, from a hopper-bottom car in one and one-fourth hours with only one attendant, while a box car takes three times as long. Power is furnished by a 7½ hp. motor. The silos hold about 600 tons and the cost on the 1916 price basis was $7000, which is considered to be $700 too high, due to unusual foundation blasting and other difficulties.

Fig. 46 shows a storage plant of the American Hominy Company of Indianapolis, Indiana. It is built of concrete in silo type and has a basement conveyor tunnel running the full length of the building. Each of the five concrete bins is 28 feet in diameter and 75 feet in

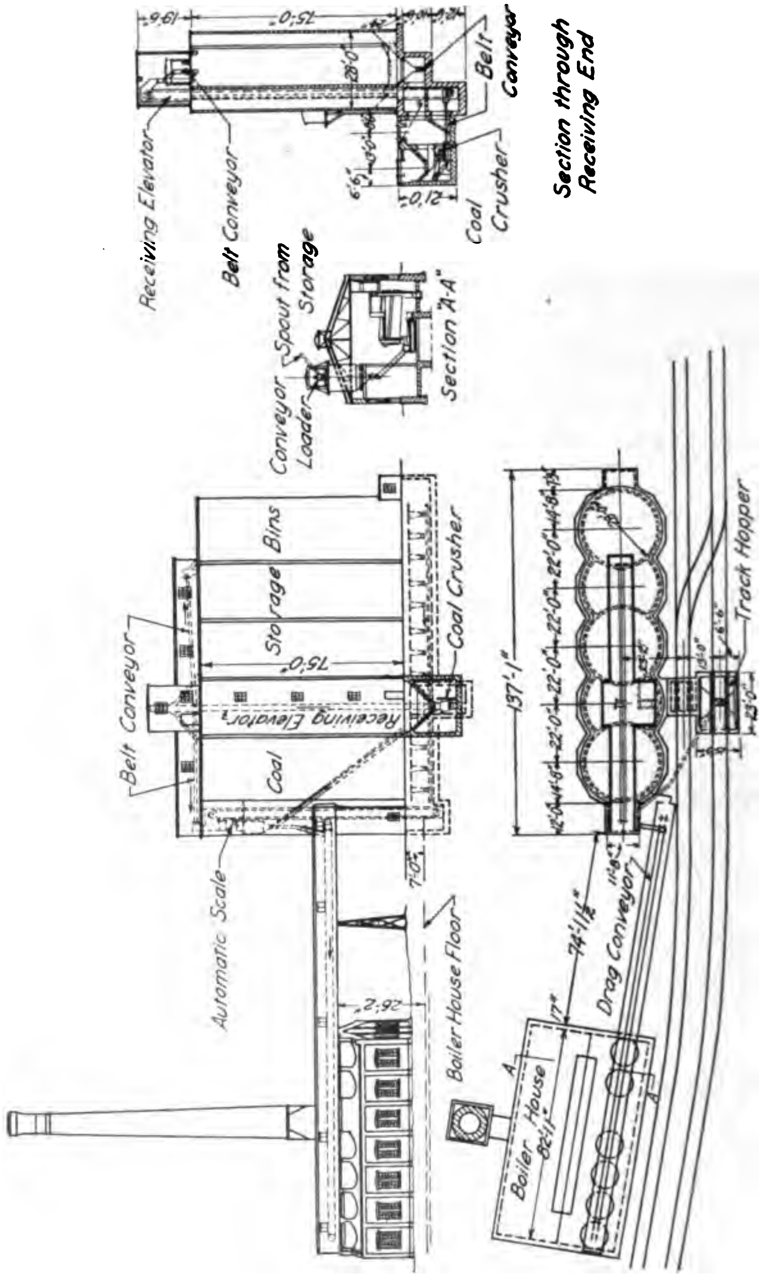

FIG. 46. SIDE ELEVATION, PLAN, AND SECTION OF COAL STORAGE PLANT OF AMERICAN HOMINY COMPANY, INDIANAPOLIS, INDIANA

height. The coal is received through a deep track hopper which will take the discharge from the longest coal car made and deliver it through a crusher to a vertical elevator which raises it to the top of the storage plant. The distributing arrangement is such that the coal may be delivered directly to the bunkers in the boiler-house or sent into the bins for storage. After being delivered into the bins it is transferred from these bins by means of a belt-conveyor located in the basement of the building, elevated by a vertical conveyor at the end, and discharged through an automatic scale to a conveyor which delivers the coal to the boiler room bunkers. The advantages claimed for this form of storage are reduction in ground space, as well as the reduction of labor cost due to automatic handling of material.

At this plant, during the summer of 1919, an explosion occurred in one of the silos while a small amount of coal that had heated badly was being drawn off at the bottom. The explosion had sufficient force to lift the roof slab a few inches and to carry away a small section of the side wall. The heating seems plainly traceable to an air leak around the outlet valves at the bottom which at first were not made airtight. After the supply of air was shut off the heating ceased.

33. *Portable and Semi-Portable Conveyors.*—The portable or semi-portable type of elevator or conveyor has been developed by a number of firms to supply means for storing and handling coal in smaller quantities and with less expensive machinery than by the use of cranes of either the locomotive or gantry type.

These appliances consist essentially of a belt or bucket conveyor suitably supported and encased and moved about by means of wheels underneath or supported by a form of trolley overhead. Semi-portable conveyors have one end fixed or pivoted, while the discharge end can be rotated. These conveyors vary in size from the small wagon loader type to the long portable type intended distinctly for storage purposes, the conveyor arm varying in length from 6 feet to 60 feet and in width from 12 inches to 24 inches. According to the catalog of the Barber-Greene Company of Aurora, Illinois, the capacity of belt conveyors and power required for different materials is given in the following table:

TABLE 17

CAPACITY OF PORTABLE CONVEYORS

Width of Belt (Inches)	CAPACITY, TONS PER HOUR					HORSE POWER MOTORS																
	Coke	Coal	Earth Clay	Cement	Sand or Stone	12′	15′	18′	21′	24′	27′	30′	33′	36′	39′	42′	45′	48′	51′	54′	57′	60′
12	10	17	29	30	34	1	1	1	1½	1½	1½	2	2	2	3	3	3	3	3	3	3	3
18	26	44	65	80	90	1	1½	1½	2	2	2	3	3	3	3	3	3	3	5	5	5	5
24	47	78	117	140	156	1½	2	2	3	3	3	3	3	5	5	5	5	5	7½	7½	7½	7½

It is claimed that, where material is delivered by gravity from the car directly to the conveyor, there is a saving of from 75 to 90 per cent in the handling cost and even where the material is shoveled to the conveyor half of the labor cost is saved. The power requirements are said to be from one to two kilowatts per hour for the short conveyors and from three to five kilowatts for the long conveyors. Several types of conveyors used in coal storage are shown in Figs. 47 to 61.

A typical method of using a combined fixed and portable system is shown in Figs. 47 and 48. The coal is delivered from the car into the boot of the fixed conveyor and at the delivery end builds up a conical pile, the height of which depends upon the height of the end of the conveyor and the amount of drop allowable. After the central

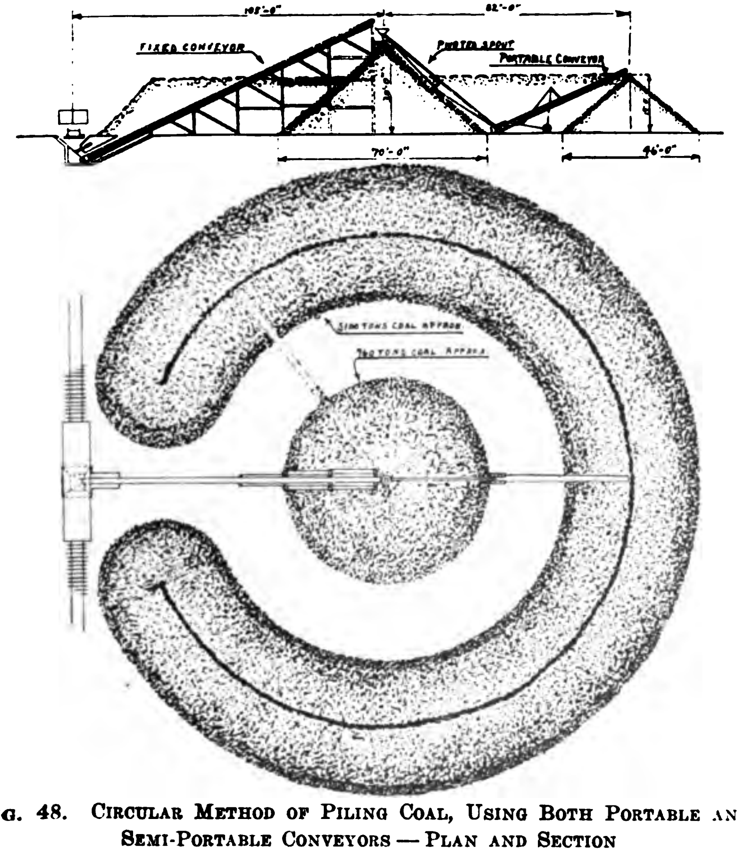

FIG. 48. CIRCULAR METHOD OF PILING COAL, USING BOTH PORTABLE AND SEMI-PORTABLE CONVEYORS — PLAN AND SECTION

pile has been built a concentric pile is built up by delivering the coal into a chute which at the bottom feeds the boot of a portable conveyor. This conveyor in turn builds up either a series of conical piles concentric with the center pile as shown in Fig. 47 or a continuous, concentric, conical pile as shown in Fig. 48.

An application of this system built by the Barber-Greene Company at Mooseheart, Illinois, is illustrated in Figs. 49 to 51. In this plant the coal is delivered from a railroad track hopper shown at the left in Fig. 49 into the boot of a vertical bucket elevator which at the top delivers the coal either into a cross-conveyor which carries it into the boiler house bunkers, or else to conveyors which carry it to the storage piles.

In the original installation built in 1918, an inclined conveyor supported on trestles was used. This conveyor delivered the coal either upon a single conical pile or, by means of a long chute and a semi-portable conveyor, upon a concentric pile or several concentric piles as shown in Figs. 49 and 50.

To reclaim the coal the process was reversed, the coal being taken from the storage pile by a portable conveyor, which delivered it to a semi-portable conveyor which, in turn, delivered it to the elevator.

Experience showed that a large central conical pile at the end of the inclined conveyor was too high for safe storage; consequently this conveyor has been lowered so that it now runs horizontally and delivers to the belt of the portable conveyor.

Fig. 51 shows the new plant at Mooseheart with four conveyors in operation. On account of the railroad cut, through which incoming cars run, it was found advisable to divide the storage equipment into two units, one on each side of this railroad. The conveyors operate with reversible motors and the receiving hopper can be changed from end to end according to whether the coal is being stored or reclaimed. The initial cost of the plant was $4600 and the cost of the storing and reclaiming is estimated to be about twenty cents per ton.

Fig. 52 shows a portable conveyor used for storing directly from a railroad car and also for reclaiming directly into a railroad car. Fig. 53 shows a portable conveyor supported by cable, and if the ground permits, this system may be extended indefinitely.

Fig. 54 shows a view of a portable conveyor made by the Automatic Coal Conveyor Company of Chicago and operated by means of an

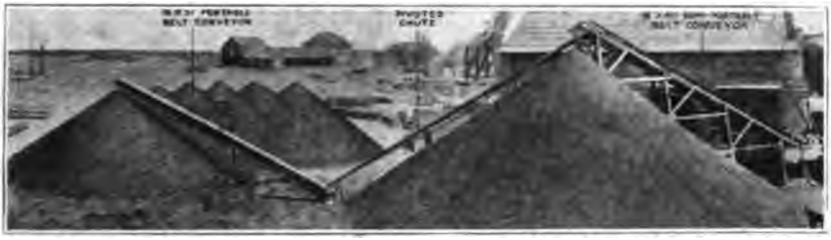

Fig. 47. Circular Method of Piling Coal, Using Both Portable and Semi-Portable Conveyors

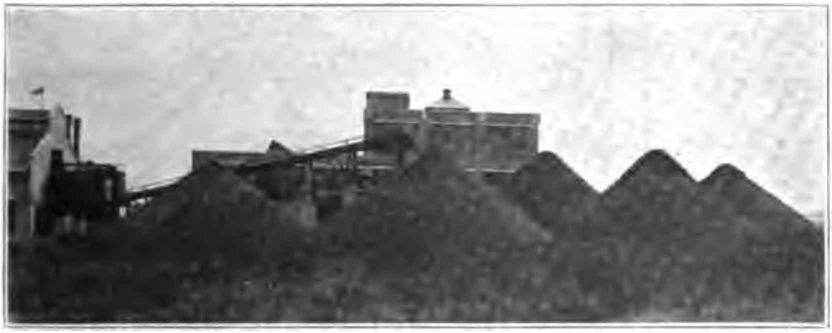

Fig. 49. Coal Storage Plant Using Fixed and Portable Conveyors at Mooseheart, Illinois

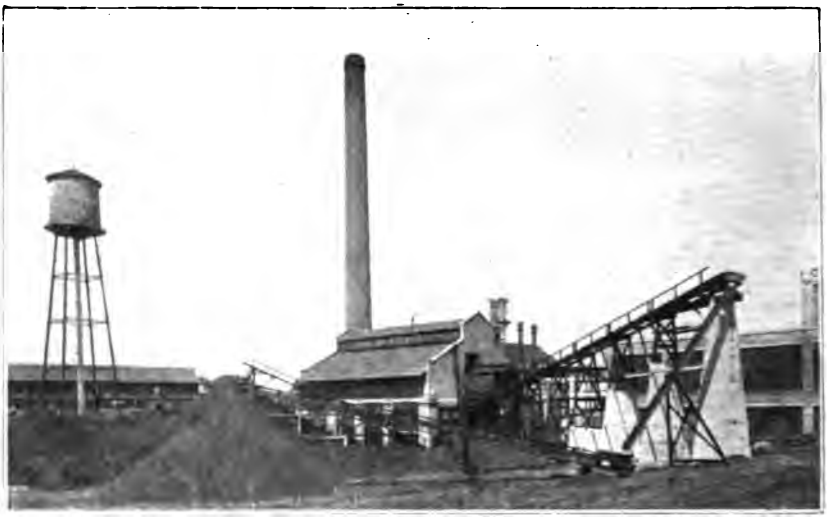

FIG. 50. COAL STORAGE PLANT USING FIXED AND PORTABLE CONVEYORS AT MOOSEHEART, ILLINOIS

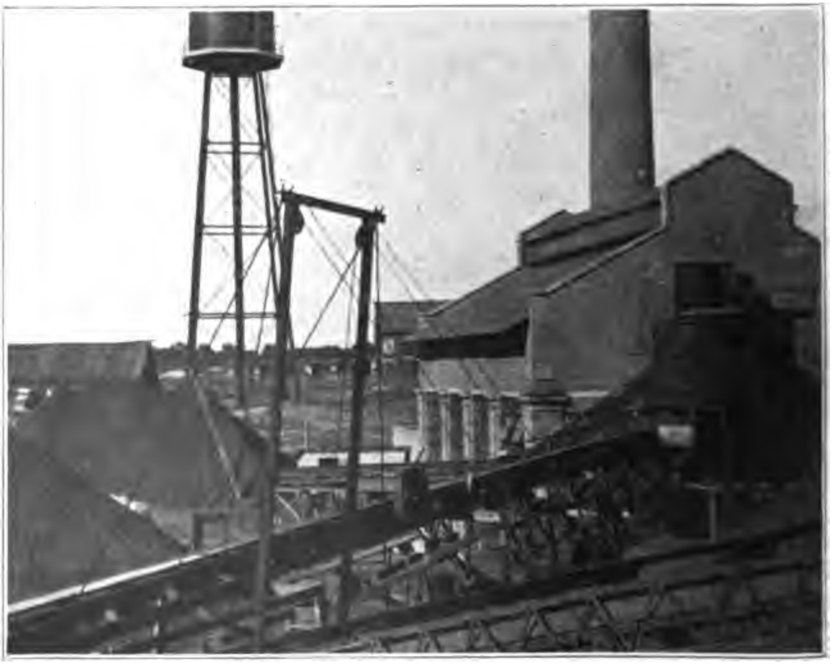

FIG. 51. VIEW OF RECENT ADDITION TO MOOSEHEART PLANT, SHOWING FOUR CONVEYORS IN OPERATION

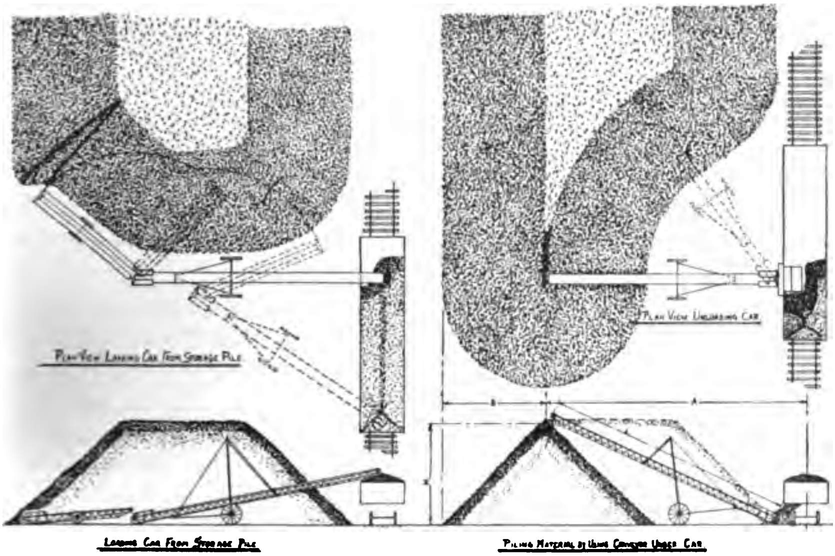
Plan View Loading Car From Storage Pile
Plan View Unloading Car
B
A
X
Loading Car From Storage Pile
Piling Material by Using Conveyor Under Car

FIG. 52. PLAN AND SECTIONAL VIEWS ILLUSTRATING METHODS OF STORING FROM AND RECLAIMING INTO RAILROAD CARS WITH PORTABLE CONVEYORS

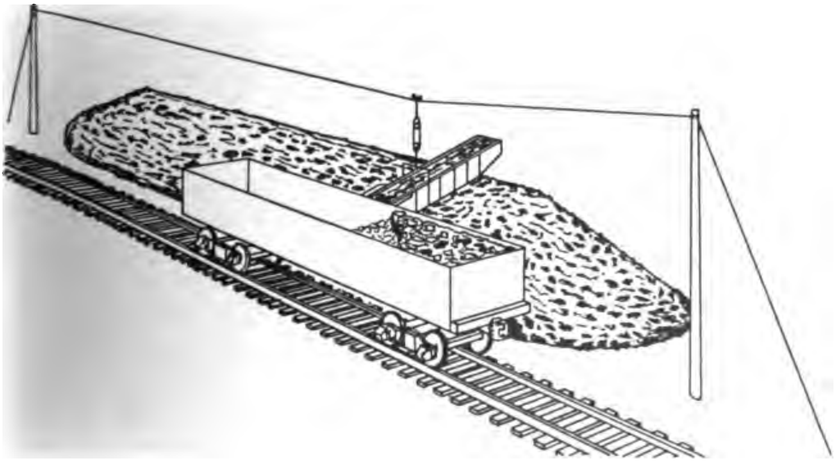

FIG. 53. PORTABLE CONVEYOR SUPPORTED BY CABLE

overhead trolley. This trolley can also be installed inside of a storage shed and used for placing coal under cover directly from the railroad car.

District of Columbia Storage Yard

The establishment of a Government coal storage yard in the District of Columbia marks a distinct epoch in coal storage. The reasons for this establishment and a description of the plant are as follows:

The Sundry Civil Act, carrying appropriations for the fiscal year from July 1, 1918, to June 30, 1919, inclusive, which was approved by the President on July 2, 1918, directed the Secretary of the Interior to establish under the Bureau of Mines a storage and distributing yard for the handling of fuel for the use of and delivery to all branches of the Federal service and the municipal government in the District of Columbia and immediately adjacent thereto, and authorized him to select, purchase, contract for, and distribute all fuel required by the said services.

This establishment was brought about as a result of the lack of adequate means for receiving and distributing coal for the use of the Government in Washington. On account of this lack of equipment. the Government was greatly handicapped in obtaining an adequate fuel supply for its buildings during the previous winter when coal production was at a low ebb and when transportation conditions, adversely affected by unprecedented weather conditions, made it impossible to get a daily supply into the city.

The annual requirements of the Departments supplied with fuel under the above legislation are approximately 400 000 tons of anthracite and bituminous coal per year. Most of the power and heating plants in which this coal is consumed do not have bunker capacity for more than a week or ten days' supply. Therefore the provision of sufficient storage space for coal to take care of all of the requirements of the Department for a period of a month seemed essential to the securing of a regular daily supply of fuel to the points of consumption.

There are periods in the middle of winter when the daily requirements for delivery of coal by trucks amount to from 2000 to 2500 tons. It seemed necessary, therefore, to provide some means of handling this large daily consumption in the middle of winter, with a minimum increase in the regular working force of the yard. The Stuart

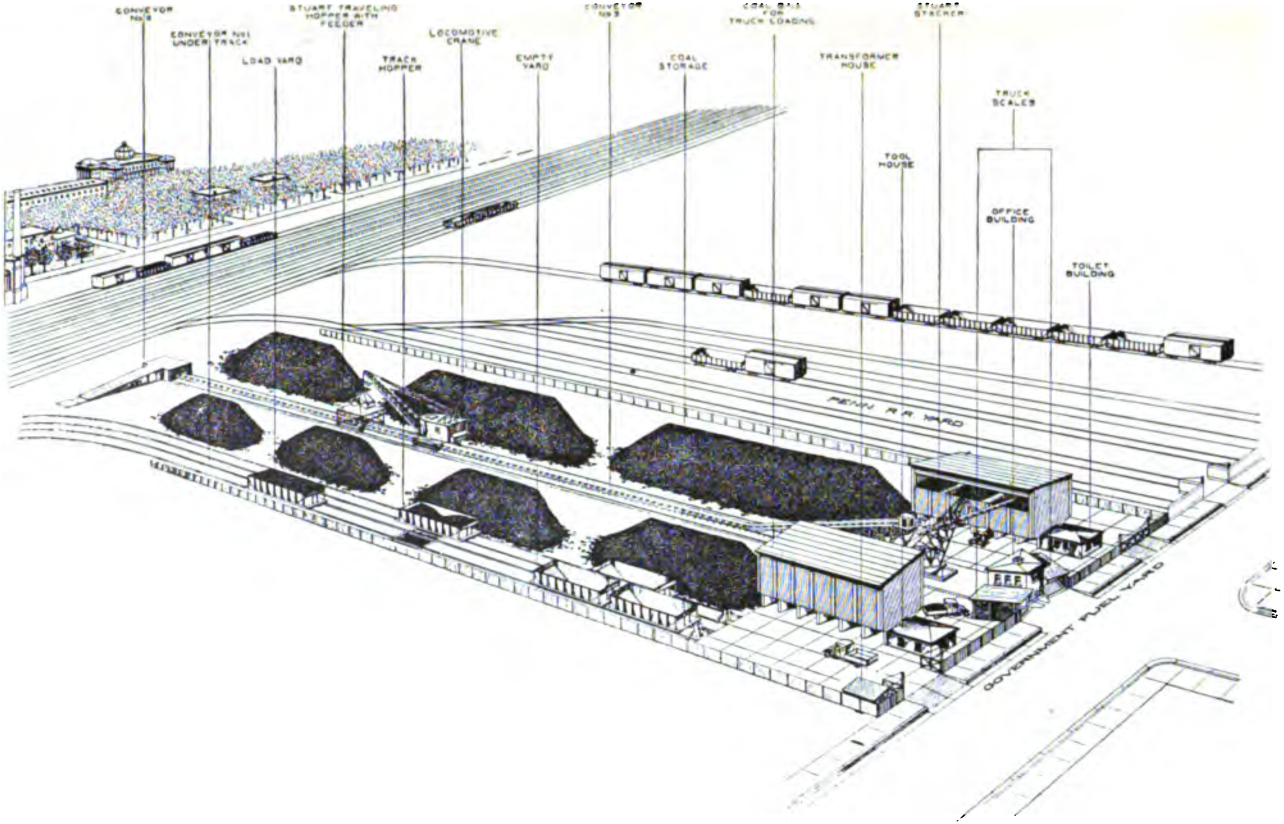

FIG. 55. GOVERNMENT COAL STORAGE PLANT, WASHINGTON, D. C. (STUART SYSTEM)

System of storage and distribution, with certain modifications to suit the conditions peculiar to the job, was selected.

Coal storage in this yard began about June 1, 1919. The storage capacity is about 30 000 tons with a capacity in the distributing bins of about 1200 tons; the plant is so arranged that the distributing equipment is not dependent for its continuous activity upon the amount of coal coming into the yard, and, on the other hand, the labor force in unloading incoming coal is not dependent upon the immediate ability of the distributing equipment to handle it.

The general arrangement and operation of the plant is shown in Fig. 55. The coal is received in self-clearing hopper-bottom cars which are dumped into a track hopper from which the coal is fed to conveyor No. 1, running in an underground tunnel, which has a capacity of 350 tons of coal per hour. The coal is weighed while in motion on the conveyor by means of a Messiter Conveyor Scale with a guaranteed accuracy of one-half of one per cent, so that the carloads of coal can be weighed separately. This conveyor delivers the coal to an inclined Conveyor No 2, shown at the left, which in turn delivers it to conveyor No. 3 (see also Fig. 56), running on the surface lengthwise of the yard. A stacker (see also Fig. 57) runs on the track and spans conveyor No. 3. It is of the portable conveyor type receiving the coal from conveyor No. 3 at any point and delivering it either to the coal bins for truck loading (See also Fig. 58) or to any storage pile alongside the conveyor. When the amount of coal received just equals the amount needed for distribution, the coal is conveyed directly to the distributing bins which are self-clearing and from which the coal flows without requiring any labor other than that of opening the valves directly into the trucks for distribution. If the amount of coal received in any one day is greater than can be placed in the distributing bins, the stacking machine which normally delivers to the bins can be withdrawn under its own power to any point in the storage yard where the surplus amount of coal received during the day can be put into storage. If, on the other hand, more fuel is required for distribution on any given day than is received in cars, the necessary amount of coal can be reclaimed from the storage space by means of a locomotive crane, which lifts the coal into a traveling hopper, whence it is fed to conveyor No. 3, and thence to the stacker and distributing bins as in normal operation.

Fig. 58 shows a general view of the office and bins from which the trucks used for distributing the coal are loaded. Mr. George S. Pope

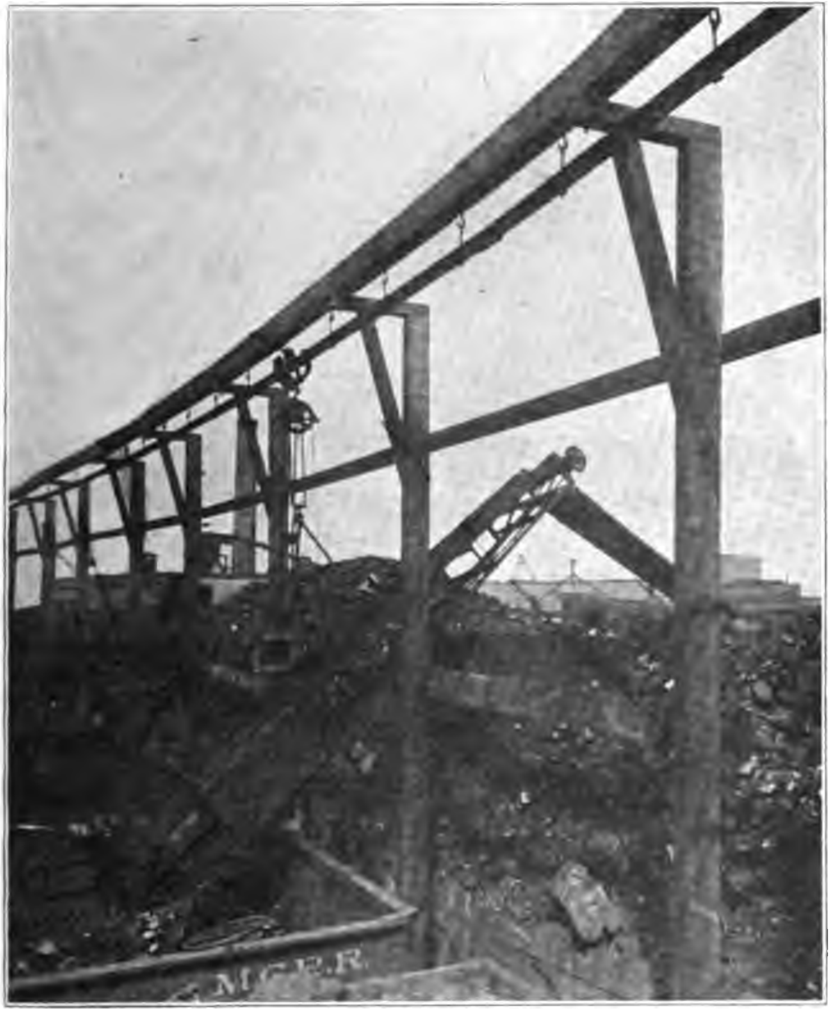

Fig. 54. Portable Conveyor Supported by Overhead Trolley

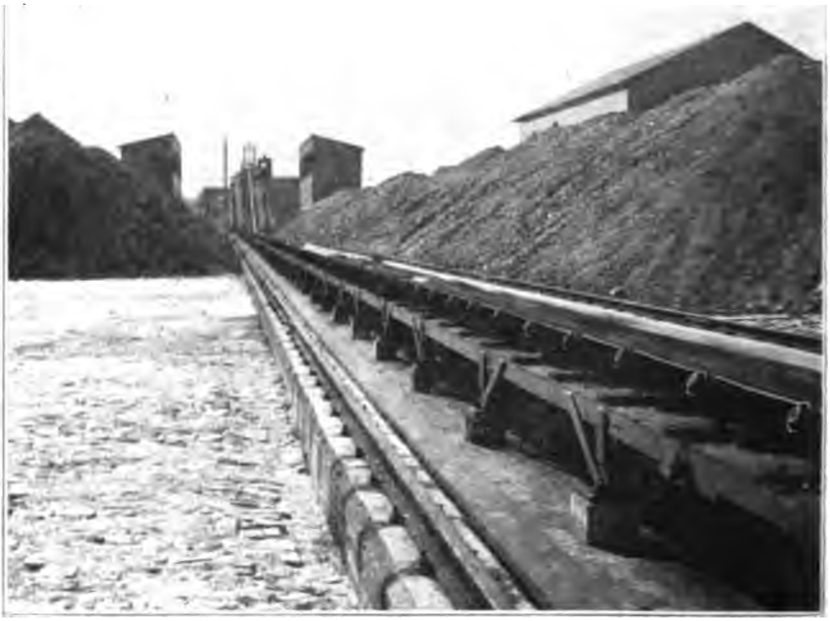

Fig. 56. Surface Conveyor, Government Coal Storage Plant, Washington, D. C.

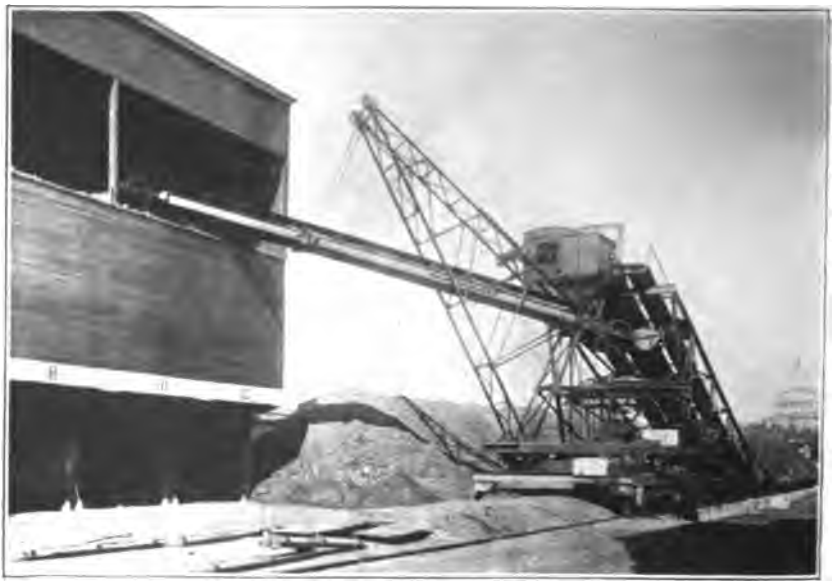

Fig. 57. Stacker, Government Coal Storage Plant, Washington, D. C.

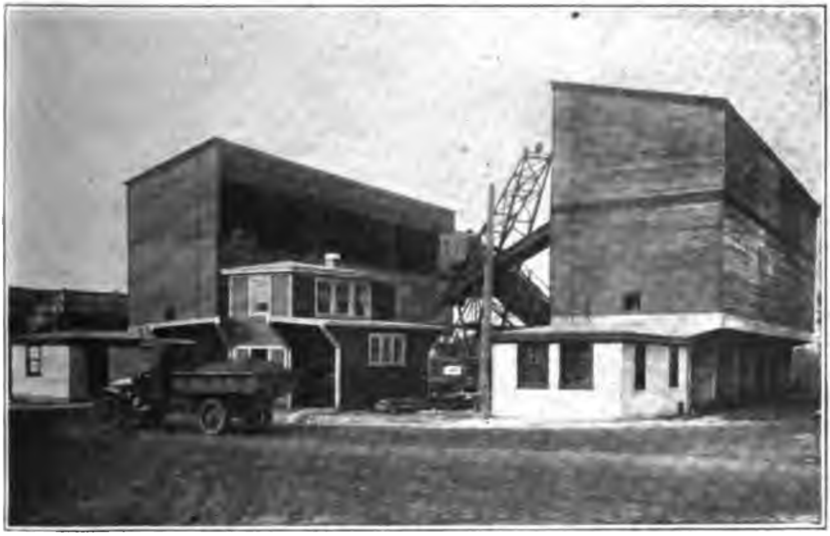

Fig. 58. Distributing Bins and Office, Government Coal Storage Plant, Washington, D. C.

of the United States Bureau of Mines, who has charge of this storage plant, reports as follows in regard to the experiences at this plant.

Four kinds of coal were placed in storage as follows:

New River coal from various mines; coal from a mine operating the Upper Kittaning or C Prime bed, Somerset County, Pennsylvania; coal from a mine operating the B or Miller bed, Cambria County, Pennsylvania; and coal from several mines in Tucker County, West Virginia. The New River and Somerset County, Pennsylvania, coals were placed in storage in June and July, and the Cambria County, Pennsylvania, and Tucker County, West Virginia, coals in September and October.

With the New River coal three or four spots indicated heat by vapors being given off, but this was easily overcome by shoveling out the coal and in no case was it necessary to dig down more than five feet. The warm coal was spread over the outside of the pile and the heat subsided. This heating took place within a month or six weeks after the coal was put in storage and since then there have been no further indications of heating in the New River coal. There have been no indications of heating in the Somerset County, Pennsylvania, coal. Within two or three weeks after it was put in storage the Cambria County, Pennsylvania, coal showed signs of heating as indicated by vapors rising from different points. Attempts were made to overcome this heating by having men shovel the hot spots out as was done with the New River coal, but as this superficial treatment was not effective, the pile was dug into with the locomotive crane and the coal used at once. In a pile containing about one thousand tons of this coal the heating became so serious that arrangements were made to put in several tractor cranes but these were not necessary. The heating seemed to be at different points throughout the pile and some coal on the verge of flaming was found within two or three feet of the surface at the top and sides as well as throughout the interior. One spot where the coal had actually burned and where ashes were found was next to the concrete floor.

The Tucker County, West Virginia, coals showed some indications of heating and were given the same superficial treatment as the New River coal, but this coal as well as all of the Cambria County, Pennsylvania, coal was moved out of storage during the coal strike. The Somerset County, Pennsylvania, coal pile was practically untouched and about one-half of the New River coal was removed.

Mr. Pope describes the several coals as follows:

> "The Somerset County, Pennsylvania, coal is about the lumpiest we have, the New River being second, the Cambria County, Pennsylvania, third, and the Tucker County, West Virginia, fourth. The Cambria County, Pennsylvania, coal has a slightly higher sulphur content than the others, its content averaging about two per cent."

The following analyses of these coals are taken from Bulletin 119, United States Bureau of Mines.

	New River, Shipments on 28 Contracts	Somerset County, Pa., Shipments on 1 Contract	Tucker County, W. Va., Shipments on 5 Contracts	Cambria County, Pa., Shipments on 16 Contracts
Moisture	1.21– 3.49	3.52	2.77– 4.09	1.82– 2.89
Volatile	16.61–23.56	15.43	17.39–24.29	19.56–22.71
Fixed Carbon	70.03–78.82	75.89	66.52–72.47	69.81–73.75
Ash	4.55– 6.57	8.68	7.87–10.14	6.30– 9.11
Sulphur	0.65– 1.00	0.92	1.02– 1.18	1.77– 2.13

The New River and Somerset County, Pennsylvania, coals were piled to a height of sixteen to eighteen feet but, by moving the stacker, the coal was piled in layers in a number of small cones so as to avoid the segregation that would result if the coal was dumped at one poin and a large cone thus allowed to build. The Cambria County, Pennsylvania, and the Tucker County, West Virginia, coals were similarl piled twenty-five feet high in places.

Erie Railroad Storage Plant

Fig. 59 shows a plan of an extensive storage plant of the Erie Railroad located at Buffalo, New York. It comprises a typical installation of the Stuart System of belt conveyors built by the International Conveyor Corporation.* The storage piles are at some distance fro the coal pockets and across the railroad yard. Two tracks for incomi coal are parallel to the two storage piles, each of which is to hold 15 0 tons, the total of 30 000 tons representing a month's supply for th coal pockets. Of these two tracks, one is for loaded and the other f empty cars. The coal is dumped through a track hopper into the h of conveyor No. 1 which delivers it to a hopper at the top of the co veyor from which it is delivered, in turn, to belt conveyor No. 2, whi runs lengthwise of the storage yard. On each side of the trough

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* A detailed description of the plant will be found in the Railway Age, Vol. 65, No p. 615.

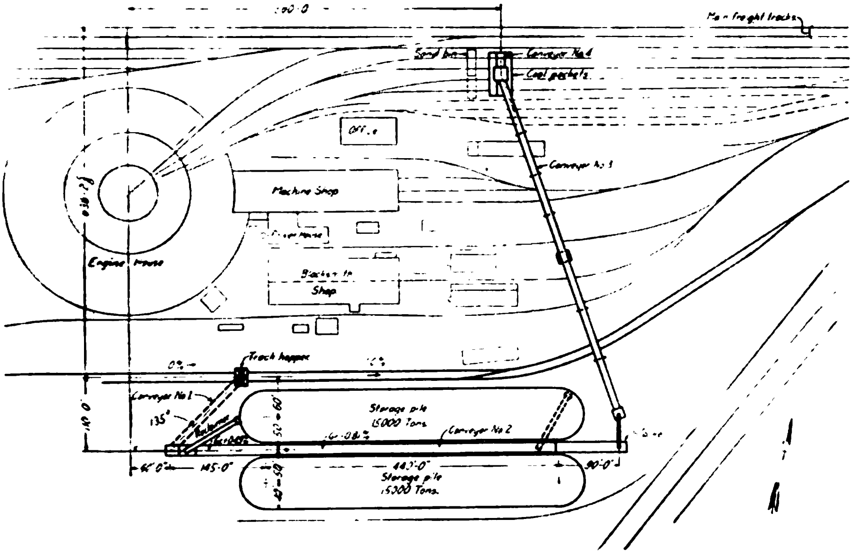

FIG. 59. PLAN OF COAL STORAGE PLANT OF THE ERIE RAILROAD, BUFFALO, NEW YORK

which conveyor No. 2 runs there is a rail; upon this rail runs a stacker which thus spans conveyor No. 2 (See Figs. 60 and 61). This stacker is essentially a movable tripper through which the conveyor belt runs and by means of it the coal can be delivered at any point along the travel of the conveyor belt. The stacker delivers to a loader running on the same track as the stacker which consists of a conveyor belt mounted on an arm that is pivoted so as to have a lateral swing of 180 degrees and a vertical movement so that the coal can be delivered with a minimum drop. The stacker in Figs. 59 and 60 is shown delivering to conveyor No. 3, which carries the coal to the coal pockets. For storing coal the stacker delivers into the storage piles.

To take coal from storage a reclaimer is used. This works on the same track as the stacker and loader, and is shown in Fig. 61. Like the loader, it is a belt conveyor operating on an arm that is pivoted on a platform and has a wide lateral swing. One end rests on the ground and a plow at the end of the arm is forced into the toe of the coal pile; the coal falling on the belt is then delivered through a hopper to conveyor No. 2 from which it is passed on to the coal pockets as previously described.

If the coal arrives at the yard faster than it is used for current coaling, it is placed in storage, but otherwise it goes directly from the track hopper through Conveyors 1, 2, and 3 to the pockets.

34. *Monorail System.*—The Godfrey Conveyor System for coal, ashes, etc., illustrated in Fig. 62, consists of a one-ton bucket or skip traveling on a suspended monorail or wire rope. The bucket is loaded by gravity at the side of the unloading railroad track. The full bucket is hoisted by means of a small electric hoist to the level of the suspended monorail or wire rope along which it is pulled by means of an endless rope operated by the electric hoist. When the dumping point is reached the bucket may be lowered to such a point that the breakage of coal in dumping will be small. The installation is designed to meet the needs of plants using from 15 to 150 tons per day and the manufacturers claim that one man can deliver about 30 tons of coal per hour either to storage or to the boiler plant. To reclaim the coal from storage, it may be shoveled into the bucket by hand, or a reclaiming bucket may be used.

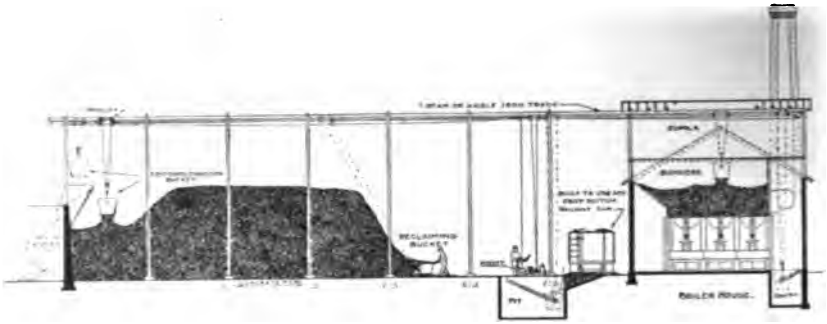

FIG. 62. GODFREY CONVEYOR SYSTEM FOR STORING AND HANDLING COAL

A monorail system of storing and reclaiming coal as used by the American Spiral Pipe Works of Chicago is shown in Fig. 63. A steel structure supports a single rail upon which operates the support for a movable clam-shell bucket. The coal is both stored and reclaimed with the same device, but the capacity is limited by the fixed position of the monorail, and the coal piled with this device forms a conical pile with the resultant segregation of sizes and increased liability to spontaneous combustion.

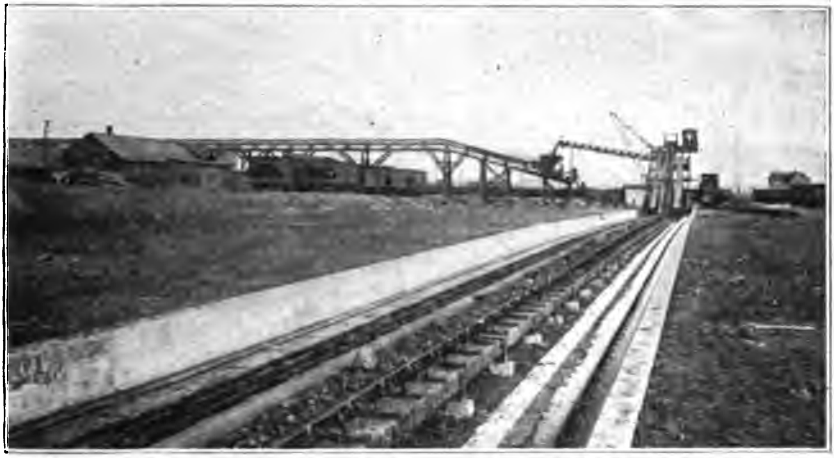

Fig. 60. View of Coal Storage Plant of the Erie Railroad, Buffalo, New York, Showing Conveyor No. 2 and Stacker Delivering to Conveyor No. 3

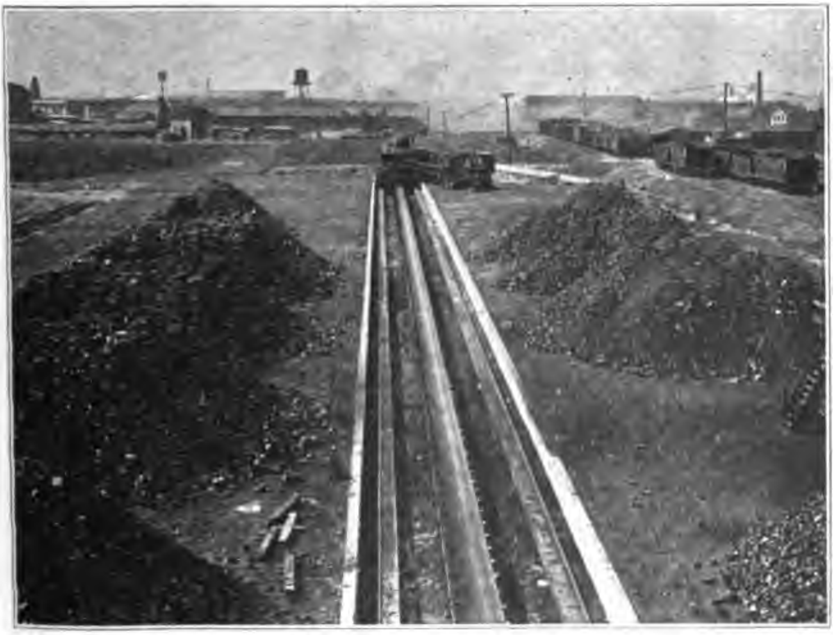

Fig. 61. View of Coal Storage Plant of the Erie Railroad, Buffalo, New York, Showing Loader at End of Conveyor No. 2

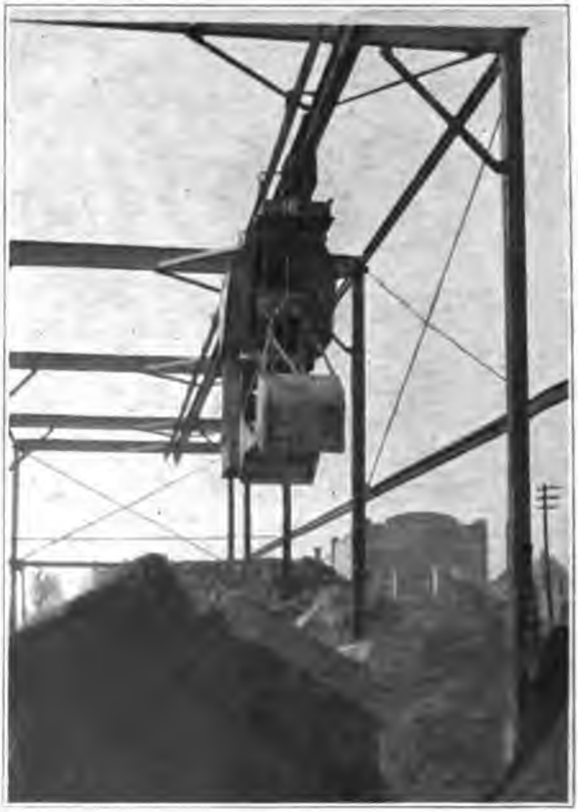

FIG. 63. MONORAIL SYSTEM FOR STORING AND RECLAIMING COAL

A similar bucket storage system has been built by the Lidgerwood Manufacturing Company, for the Galveston Coal Company, for unloading coal from steamers and conveying the coal to a storage pile. From the storage pile the coal is reclaimed and loaded into barges and railroad cars. The system consists of a self-filling bucket of the grab type which is moved along a fixed overhead track by means of rope haulage. The capacity of the Galveston installation is about 700 tons per day.

35. *Cableway System.*—The cableway system for storing and reclaiming coal consists of a hoisting and a conveying device, the latter operating over a single span cable supported by a tower at each end. The load may be taken from any point, conveyed in either direction, and deposited wherever desired along the line of the cableway.

The cableways are built in various types to meet different requirements, (a) with both towers fixed, as is Fig. 64; (b) with both towers

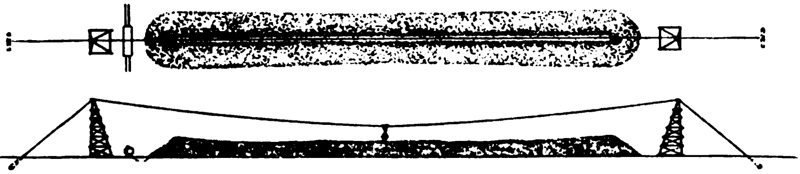

FIG. 64. CABLEWAY SYSTEM FOR HANDLING COAL — BOTH END TOWERS FIXED

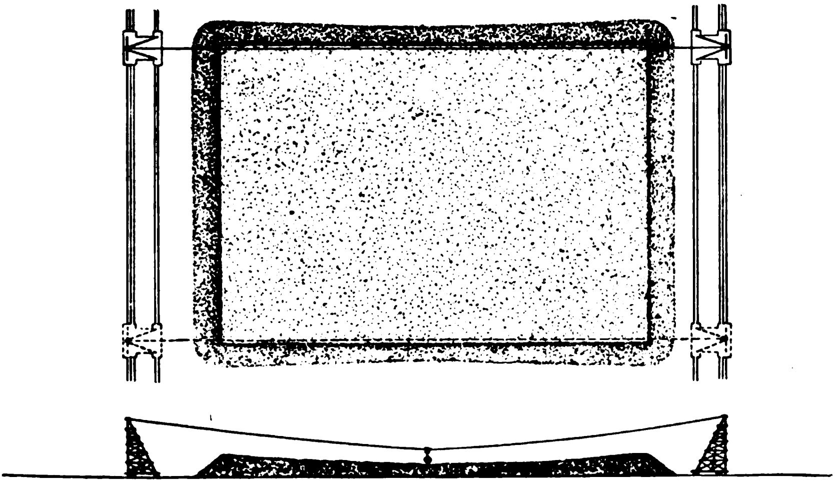

FIG. 65. CABLEWAY SYSTEM FOR HANDLING COAL — BOTH END TOWERS MOVABLE

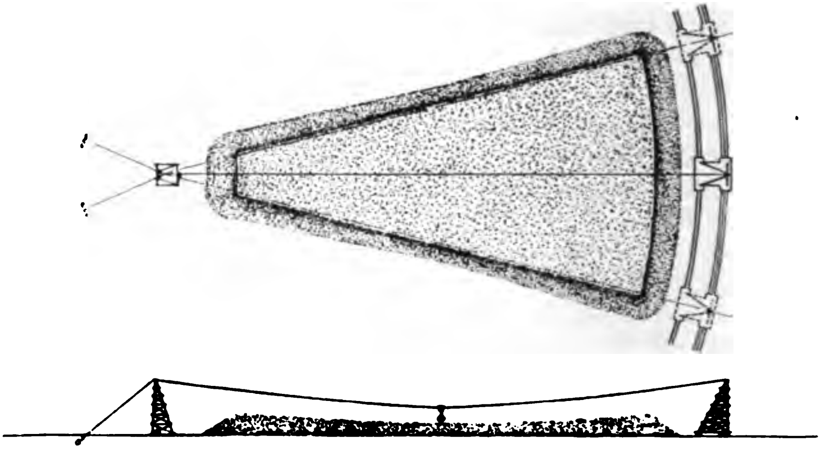

FIG. 66. CABLEWAY SYSTEM FOR HANDLING COAL — ONE END TOWER FIXED, THE OTHER MOVABLE

traveling on parallel tracks, as in Fig. 65; (c) with one tower fixed the other traveling on a circular track about it as in Fig. 66.

36. *Automatic Dump Car Storage.*—The coal storage plant of the Karm Terminal Company at Bridgeport, Connecticut, installed by the Bergen Point Iron Works of Bayonne, New Jersey, is shown in Fig. 67. The coal is unloaded from barges by cranes as shown and dumped into automatically dumping electric cars which discharge either into a storage pile, into railroad cars, or into a coal pocket. Coal is reclaimed from the storage pile by another set of electric cars running through tunnels underneath the pile. These cars either take the coal to a loading pocket for loading automobile trucks or dump the coal into railroad cars, about twenty of which can stand underneath railroad viaducts. These railroad cars can all be loaded without being moved, as the small car can be made to dump automatically at any point.

37. *Cristobal and Balboa Coaling Stations.*—The coaling stations located at Cristobal and Balboa at the two ends of the Panama Canal are shown in Figs. 68 and 69. These were built by the Bergen Point Iron Works of Bayonne, New Jersey, and represent advanced practice for the handling of coal. The combined storage capacity of the two is 700 000 tons. At Cristobal Station 1200 tons per hour can be

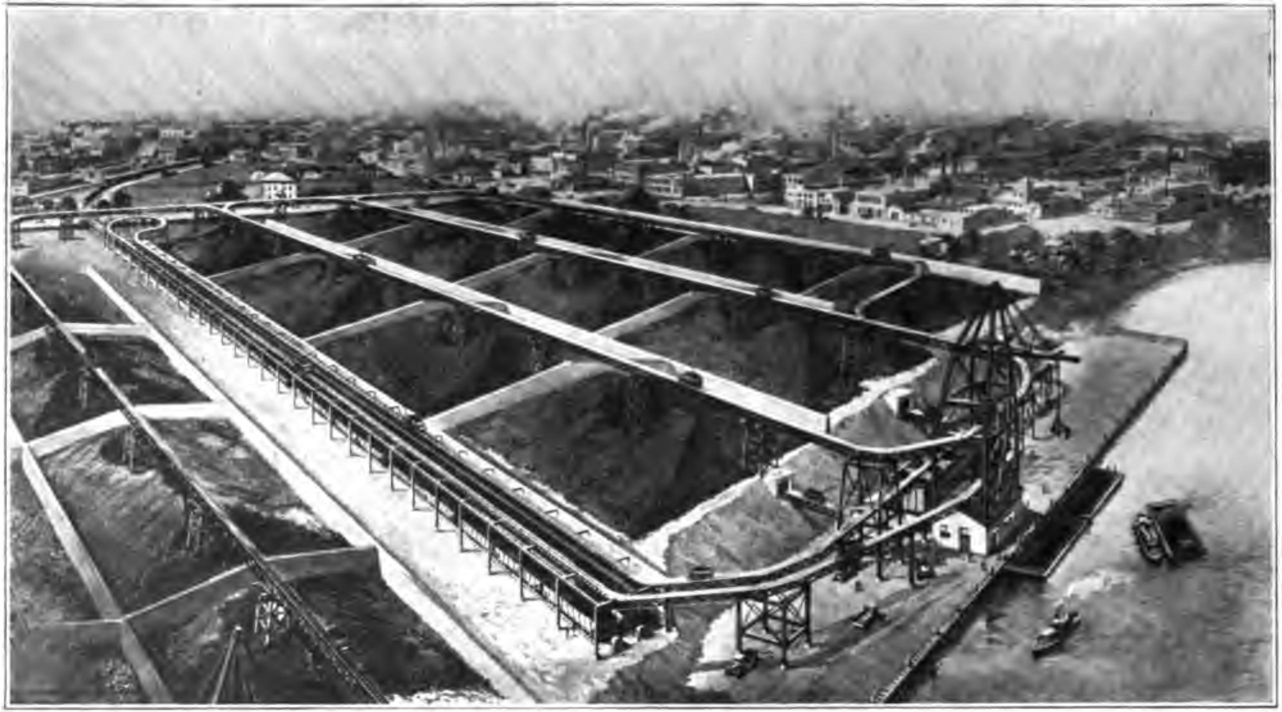

Fig. 67. Coal Storage Plant of the Karm Terminal Company, Bridgeport, Connecticut

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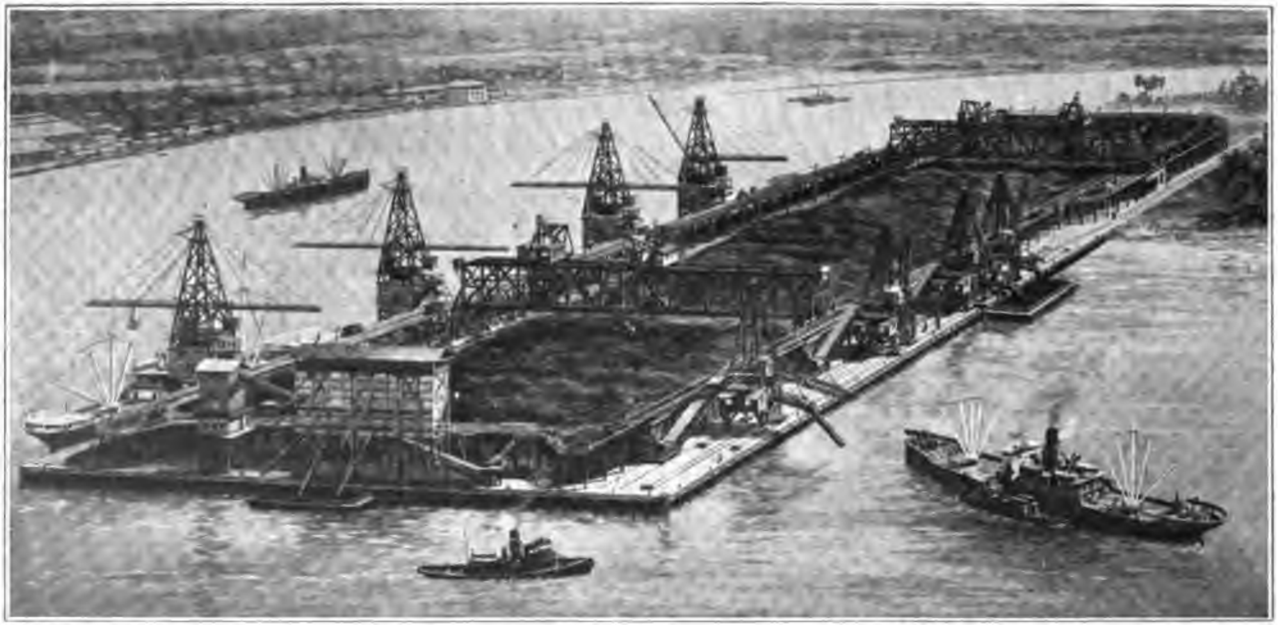

FIG. 68. THE CRISTOBAL COALING STATION, PANAMA CANAL

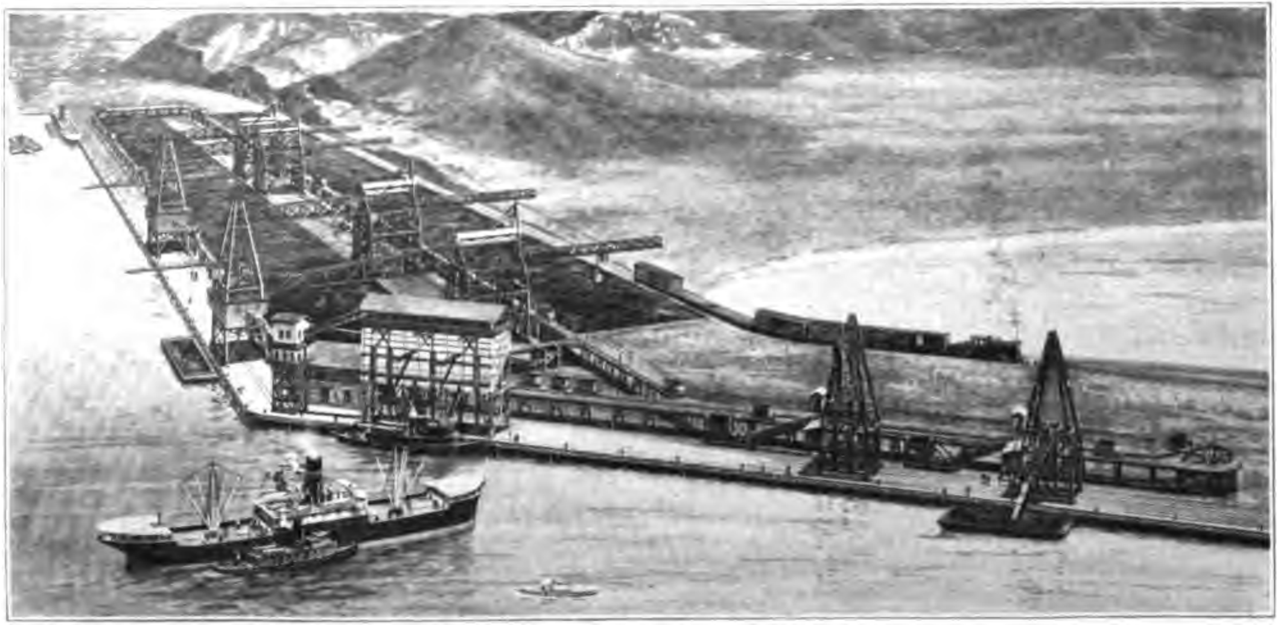

FIG. 69. BALBOA COALING STATION, PANAMA CANAL

unloaded and 2400 tons per hour reloaded. The storage plant includes both underwater and dry storage. The general layout of the plant is shown in the photographs; a number of articles descriptive of the detailed construction have been published.*

For the unloading and stocking, coal is taken from colliers or barges by unloaders equipped with 2½-ton buckets which have a rated capacity of 250 tons per hour. The coal is taken from the un-loaders to the dumping point by cars. It is reclaimed from storage by reclaiming bridges, each of which is equipped with a 5-ton bucket, having a rated capacity of 500 tons per hour. The total handling capacity at Balboa is only half that at Cristobal.

38. *Suction Conveyor.*—An application to coal storage purposes of the suction conveyor for handling coal and ashes at a power plant as used by the Pierce-Arrow Motor Car Company at Buffalo, New York, is shown in Fig. 70. Coal is taken from a track hopper by suction to a 100-ton coal tank from which it is delivered by motor-driven cars to the bunkers above the boilers. As is shown in Fig. 70 a reserve storage of 3000 tons is provided at one end of the plant by continuing the track and delivering coal from the coal tank in the motor driven cars to a storage pile instead of to the bunkers. Coal from the storage pile is reclaimed by permitting it to run into an underground reclaiming duct from which it is sucked into the 100-ton coal tank. At this plant bituminous screenings are used.

39. *Mine Storage.*—At Aldrich, Alabama, the Montevallo Mining Company operates a longwall mine with convict labor. In order that the mine might be operated six days a week with a variable supply of

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* "Coaling and Supply Depots at Panama." Black Diamond, Vol. 49, No. 25, p. 20, Dec. 21, 1912.

"Coaling Plants at Panama Canal." Coal Age, Vol. 3, p. 481, 1913.

"Panama Canal's Big Coaling Station." Coal Trade Bulletin, Vol. XXXV, p. 31, Oct. 2, 1916.

"Coaling at the Panama Canal—Cristobal," by F. J. Warden-Stevens. Colliery Guardian, Vol. CXII, p. 745, Oct. 20, 1916.

"Coal at the Panama Canal—Balboa," by F. J. Warden-Stevens. Colliery Guardian, Vol. CXII, p. 789, Oct. 20, 1916.

"Panama Canal Coaling Plants." Coal Trade Bulletin, Vol. XXXVI, p. 43, Apr. 2, 1917.

"Uncle Sam's Great Storage Docks." (Panama). Coal Trade Bulletin, Vol. 39, pp. 37-38, Oct. 15, 1918.

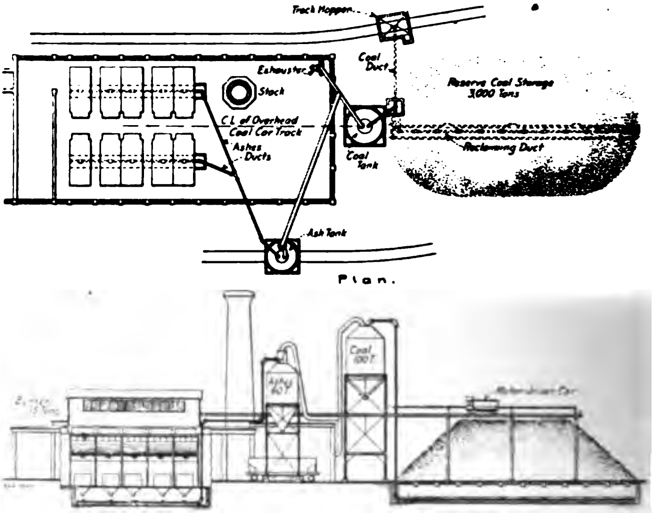

FIG. 70. SUCTION CONVEYOR COAL STORAGE PLANT OF THE PIERCE-ARROW MOTOR CAR COMPANY, BUFFALO, NEW YORK

railroad cars, a storage method was introduced. The general arrangement is shown in Fig. 71. Railroad cars loaded at the tipple are run by gravity several hundred feet to a suitable storage ground where the coal is shoveled out of the cars by hand labor or drawn from the bottom with hopper-bottom cars. When as much coal as possible has been stored in this way a wall is built of the larger lumps carefully piled along the railroad tracks. Planks placed on top of these walls and on top of the gondolas furnish a runway for the wheelbarrows which are loaded from the cars and dumped at the edge of the pile. The total capacity is about 20 000 tons and the cost of unloading approximately eleven cents per ton. The coal is reclaimed into one-ton mine cars running on a track at the foot of the storage pile as shown. These cars are pulled by a gasoline locomotive and hoisted three at a time up an incline into a revolving dump where the trip of three is emptied without uncoupling. The cost of reclaiming is ten cents per ton.

These costs will probably be decreased by the use of another rotary dump instead of so much hand-labor and if side-hill storage were used the cost of loading into the one-ton cars could be saved.

A belt conveyor has been built at Fairpoint, Ohio, by the Roberts and Schaefer Company of Chicago for the Clarkson Coal Mining Company of Cleveland, Ohio. This belt conveyor is supported on a trestle

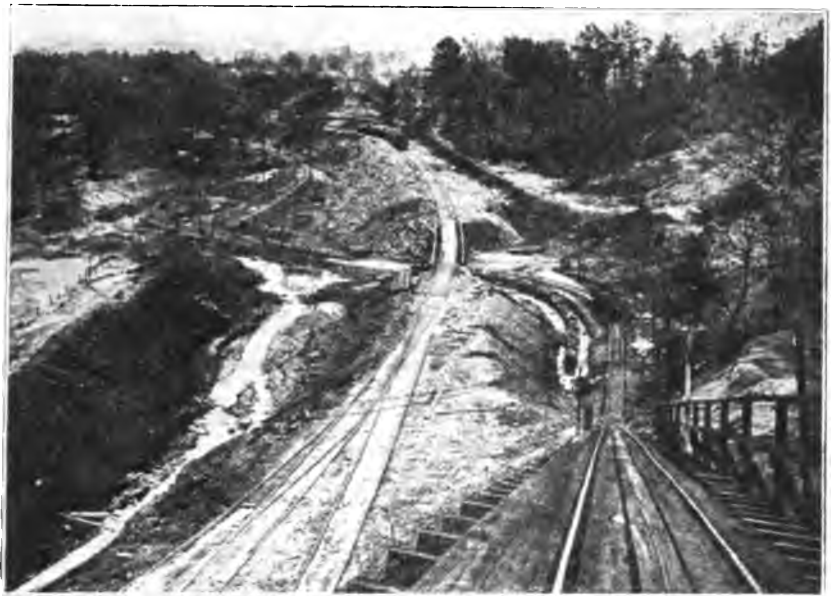

FIG. 71. STORAGE SYSTEM USED BY THE MONTEVALLO MINING COMPANY, ALDRICH, ALABAMA

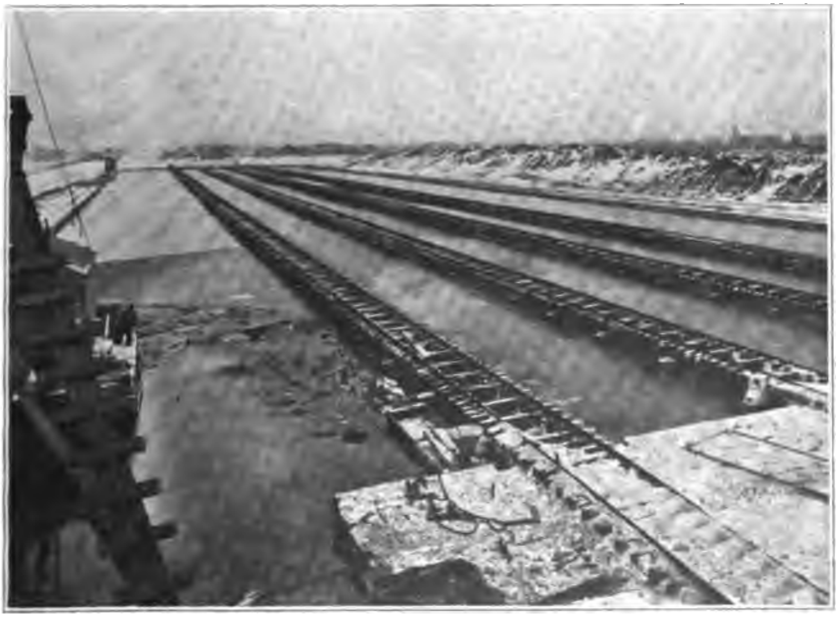

FIG. 72. UNDERWATER COAL STORAGE PLANT OF THE STANDARD OIL COMPANY, WHITING, INDIANA (100 000 TONS CAPACITY)

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[illegible]

for storing the slack, which is taken from beneath the screens, and by means of a tripper is dumped on the ground beneath the trestle. The coal is reclaimed with a locomotive crane. The plant has a capacity of 40 000 tons and 300 tons per hour can be handled. Lump, three-quarter, mine-run, and slack can be stored. The plant is intended for storage purposes when the car supply is low so that a full day can be run at the mine.

40. *Underwater Storage.*—

Duquesne Light Company Storage Plant

The Duquesne Light Company, Pittsburgh, Pennsylvania, completed during the fall of 1917 a large reinforced concrete storage basin at the Brunot Island power plant.*

The storage basin which is adjacent to the power plant, and between it and the main channel of the Ohio River, is 791 feet long, 153 feet wide, and 25 feet, 6 inches deep, the side and end walls sloping at an angle of 45 degrees. The basin has a capacity of 100 000 tons of submerged coal and 150 000 tons with the coal piled above the water-line. The side and end walls of the basin taper from 18 inches at the bottom to 8 inches at the top.

As the bottom of the basin is below the normal river level, special provision had to be made for the lifting pressure that would be exerted on the bottom of the basin at high water stages, the soil being coarse gravel and very porous. The bottom which is 18 inches thick is made of 30 main reinforced concrete slabs each 51 feet square. These slabs rest on reinforced concrete curbs the bases of which are 4 feet square and 12 inches thick; the bridge extending up from the base is 15¼ inches high and 6 inches wide. These curbs, besides supporting the bottom, also allow for expansion and contraction of the concrete slabs. All joints are filled with pitch. The plant condenser-water discharge duct which is constructed of concrete divides the basin into two sections. The fact that the top of the duct is 7½ feet above the concrete bottom permitted one-half of the basin to be used while the other half was being constructed.

Water for flooding the basin is admitted through 12-inch filling holes and is supplied by one of the plant condenser circulating pumps, equipped with a discharge pipe for this purpose. Four 18-inch independent drain pipes which extend to the river are each equipped with a gate and a check valve, and with a by-pass around the latter. The basin can be drained by opening the gate valves. This arrangement permits the automatic flooding of the coal basin with river water to relieve the upward pressure on the concrete bottom. Should the river rise much above normal, water will flow into the basin to a height corresponding to that of the river. When the river subsides the water may be drained from the basin if desired. At the present time no figures with respect to the operating cost of the storage basin are available.

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* Power, page 651, Nov. 13, 1917.

Underwater Pit of the Standard Oil Company, Whiting, Indiana*

Figs. 72 and 73 show an underwater storage pit built by the Great Lakes Dredge and Dock Company of Chicago, Illinois, for the Standard Oil Company about two miles south of the shore of Lake Michigan at Whiting, Indiana. This storage pit has a capacity of 100 000 tons.

The storage basin consists of a pit 1000 feet long, 202 feet wide, and 28½ feet deep below yard rail level and 24½ feet deep below ground water level. The pit is enclosed by a heavy wooden sheet-pile dock construction below water level, capped with concrete above water level. There are four lines of standard gauge railroad track trestle running longitudinally through the pit and four lines on each side of the pit.

The pit was excavated with a 15-inch hydraulic suction dredge, which was hauled overland a mile and a half to the site; advantage was taken of the marshy conditions to excavate a sufficiently large area in which to float the dredge. The excavated material was discharged through pipes at a point 1000 feet away from the pit and the run-off water carried back to the pit through trenches; thus a sufficient supply of water was insured to keep the dredge afloat. Wakefield sheet-piling and dock-piling were then driven by means of two floating pile drivers, built on the site, and the concrete mass surrounding the pit at the water line was placed, special concrete mixers being mounted on railroad flat cars. The bottom of the pit was leveled off with the hydraulic dredge by means of a special mouth-piece, so that no point was more than six inches above or below grade. After the dredge had leveled off

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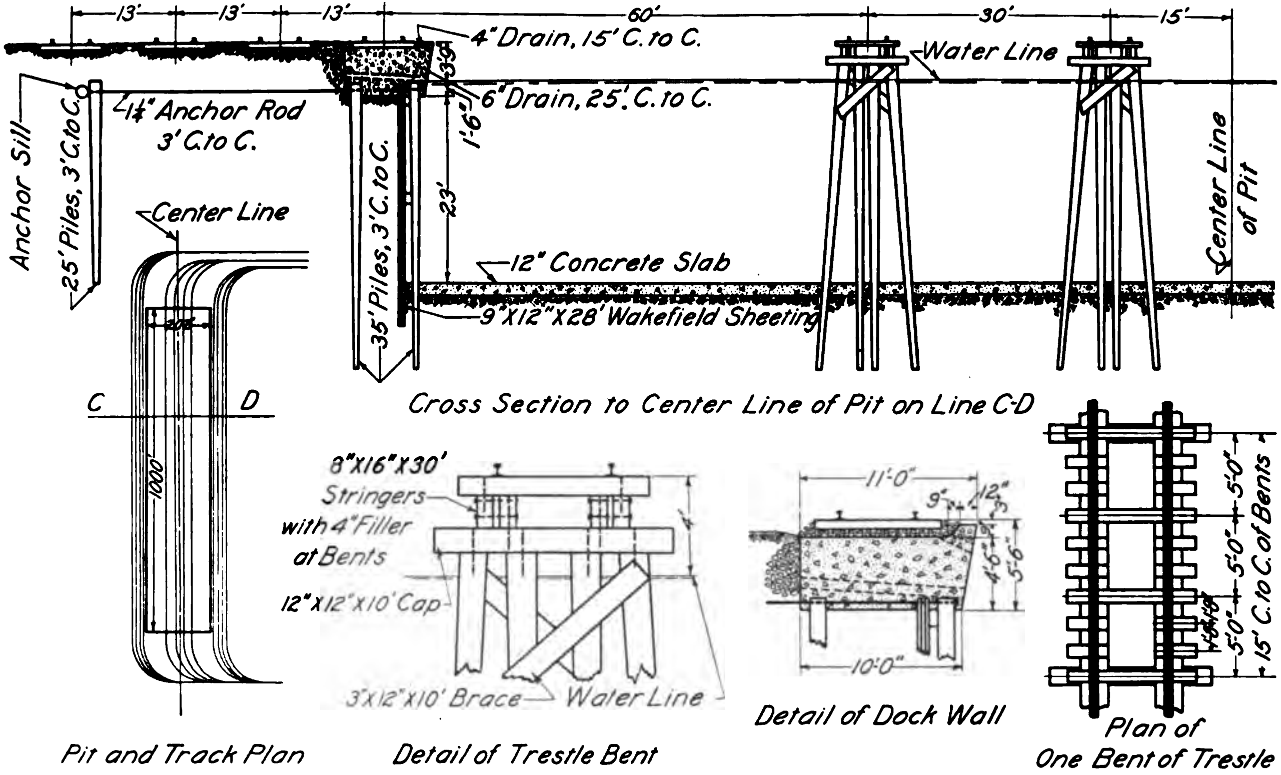
* See also Circular No. 6, p. 103.



Cross Section to Center Line of Pit on Line C-D

Pit and Track Plan

Detail of Trestle Bent

Detail of Dock Wall

Plan of One Bent of Trestle

FIG. 73. UNDERWATER COAL STORAGE PLANT OF THE STANDARD OIL COMPANY, WHITING, INDIANA — SECTIONAL VIEW AND DETAILS

the bottom, a drag was used consisting of a heavy horizontal 12 feet by 1 foot timber fastened to a pile driver.

The concrete floor, one foot in thickness was placed in about 25 feet of water over the entire floor area of 1000 feet by 202 feet, by means of a special tremie device, patented by the Great Lakes Dredge and Dock Company. By using this device, it was possible to place the concrete under pressure and to spread it uniformly over the bottom, so that no point was more than three inches off grade.

The following advantages are claimed for this form of pit construction:

1. Lower cost than for all concrete or wood-and-concrete construction.
2. Lower cost of unloading coal by dumping from trestles and from tracks along the sides of the pit than by using grab-buckets operated by a bridge or crane. The bulk of the unloading cost consists in dumping the cars (either bottom or side dump) from the trestles or from the side of the pit, leaving a very small portion to be unloaded with yard cranes.

This method permits the use of different sizes of locomotive cranes where they are available around any plant.

By means of the four tracks running through the pit and those on each side, six trains, of at least twenty 50-ton coal cars can be unloaded or loaded simultaneously.

The four tracks in the pit and those along each side give a trackage length of practically two miles for rail storage purposes; in other words, little ground space is lost by installing one of these pits in this manner. In fact, any switch yard can have an underwater coal storage pit without the acquisition of more land.

APPENDIX I.

QUESTIONNAIRE *A*

1. What kind of coal was stored? ....
2. What size of coal was stored? ....
3. Was all of the coal stored of same size and kind? ....
4. What amount of coal was stored? ....
5. State from what mining district and if possible from what mine the coal came:..
6. Size of pile: Depth............; Length............; Breadth..........
7. Describe the method of unloading and storing:...........................
....
8. Was coal unloaded, by crane, drop bottom car, hand?..................
9. What trouble have you had from fires in your coal pile? ....
10. How much of the coal was destroyed by fire? ....
11. What in your opinion was the cause of the fire? ....
....
12. What evidence have you upon which to base this opinion? ....
....
13. How long had the coal been in storage when the fire was observed? ....
14. Was the coal actually ablaze or only smoking? ....
15. Was the temperature taken? .... What was it? ....
16. Where in the pile did the fire start? ....
17. How was the fire controlled or extinguished? ....
18. Was any attempt made to ventilate the pile; if so, how? ....
19. Was there any damage to adjacent structures? ....
20. Information furnished by:..

....
(Official title and Company)

....
(Address)

General Remarks:
....

Please use reverse side of this sheet for any general remarks and suggestions.

QUESTIONNAIRE *B*

Please answer the following questions and mail your answers direct and as soon as possible to Professor H. H. Stoek, Department of Mining Engineering, University of Illinois, Urbana, Illinois.

1. What kind of coal was stored? ....
2. What size of coal was stored? ....
3. What amount of coal was stored? ....
4. State from what mining district and
   if possible from what mine the coal came:..
5. The size of pile: Depth..........; Length..........; Breadth..........
6. Describe the method of storing:..
   ....
   ....
7. Have you had any difficulty
   from fires in your coal pile? ....
8. How much, if any, of the coal
   was destroyed by this fire? ....
9. What in your opinion was the cause of the fire? ....
   ....
10. What evidence have you upon
    which to base this opinion? ....
11. How long had the coal been in storage
    when the fire was observed? ....
12. Was the coal actually ablaze or only smoking? ....
13. Where in the pile did the fire start? ....
14. How was the fire controlled or extinguished? ....
15. Was any attempt made to ventilate the pile; if so, how? ....
16. Was there any damage to adjacent structures? ....

Information furnished by:

....
(Company)

....
(Address)

....
(City and State)

For general remarks use back of this sheet.

DATA SHEET

Date........................

Name and address:..
Party interviewed:..
Size and kind of coal:..
Mine or district:..
Name of shipper:..
Is coal correct size? ....
Amount of sulphur:..
Method of piling:..
Tonnage and dimensions of pile:..
How long in storage? ....

VENTILATED:..

WHERE DID FIRE START? ....

WAS WATER USED? ....

PICTURE:..

HOW WAS FIRE HANDLED? ....

PROBABLE CAUSE OF FIRE:...

REMARKS:...

APPENDIX II

RAILWAY ADMINISTRATION STORAGE CIRCULAR

The following circular of instructions for the storage of coal was sent by the government to all railroads in the United States. It is, undoubtedly, the most comprehensive effort to safeguard and stimulate the storage of coal ever made in an industry.

The Storage of Coal

TO OPERATING OFFICERS IN CHARGE OF COAL STORAGE:

The standing committee on the storage of coal, appointed by the International Railway Fuel Association, has made a number of recommendations which are contained in the transactions of the association for the year 1909 to 1917, inclusive.

An exhaustive study of the storage of bituminous coal was also made by H. H. Stoek, professor of mining engineering of the University of Illinois, Urbana, Ill., and published March 4, 1918, in Circular No. 6 of the Engineering Experiment Station of that university.

A further circular covering additional features in the storage of bituminous coal will be published and ready for general distribution within a few months. In the meantime Professor Stoek is preparing a paper on the storage of bituminous coal to be read at the eleventh annual meeting of the International Railway Fuel Association convening in Chicago in May next.

From this information, and that which has been furnished by the United States Railroad Administration, certain suggestions have been gathered covering the proper method of storing railroad coal which, if applied, will assist in keeping the cost of storage to the minimum, and will result in greatly reducing or entirely eliminating the hazard caused by spontaneous combustion.

From necessity no general rule can be made which will fit the various coals stored in the different sections of the country, and railroad officials in charge of this work will be compelled to exercise a reasonable measure of discretion in carrying out any recommendations of a general character that may be made.

Why Railroads and Other Consumers Should Store Coal

1. To insure an ample supply for locomotives and miscellaneous steam purposes during period of reduced delivery occasioned by cessation of water-borne traffic, mine strikes, extremely rigorous winter weather, periods of serious car shortages, etc.

2. So that a partial equalization of the coal-car supply may be made. The excess demand for railroad and commercial coal during the fall and winter season, accentuated by a decreased daily car mileage, invariably leads to a car shortage during that period, with a resulting surplus during the summer season, when coal is ordinarily stored.

3. The cost of transporting railroad coal during the summer season is estimated as not exceeding 60 to 65 per cent of the cost of such movement during the period of extreme winter weather, during which time if the carrier is relieved, if only in part, of the transportation of railroad coal, the locomotives, cars, and coal thus made available can be diverted to commercial consumers, with resulting revenue advantage.

How to Store Coal

The actual work incident to the storage of railroad coal should only be undertaken after a study of the subject has been made by some responsible official, who should, after conferring with the proper representatives in charge of purchase, transportation, and maintenance, formulate such definite plans as will insure the full co-ordination of every man responsible for any portion of the work to be done; to this end the following points should be given careful consideration:

(*a*) Determine the amount of coal which should be stored, beginning May 1, ending August 31, except in the case of water-borne coal, where the storage period will be governed by the navigation season. The rate of storage daily and weekly should be prescribed in order to prevent an under or over supply at the storage station. Storage points remote from the source of supply should be given preference.

(*b*) As far as possible, avoid purchasing coal for storage that bears the reputation of firing when stored.

(*c*) Store screened lump coal where such is obtainable, 4-inch or 6-inch lump preferably, the portion passing through the 4-inch or 6-inch screen openings to be used for current consumption during the storage period. Coal placed in individual storage piles should come from as few mines as possible. In no case mix coal from different districts or from different seams located within the same district.

(*d*) Before undertaking storage select a suitable location as near as possible to the point of consumption, avoiding hillsides, rough ground, and soft, wet, boggy ground in particular. The storage location should be thoroughly cleaned of all refuse matter, giving particular attention to the removal of vegetation, wood, discarded waste, old clothes, or other similar combustible matter which would assist in starting stock-pile fires or would depreciate the value of the coal when loaded out. Do not pile above a steam pipe, over a sewer trap, or against a hot wall. Positive provision should be made for draining the ground so that water may not accumulate under the pile.

(*e*) It is now well established that coal fires spontaneously by the oxidation of the fine particles, which present the maximum surface for the air to act upon, well-screened coal carefully piled seldom firing, for the reason that a minimum surface is subjected to oxidation, the openings between the lumps admitting of any heat engendered passing off. Fires usually start in piles where the coal is more or less separated in coarse and fine strata, the air entering through the coarser strata acting on the finer portion, which is too dense to admit of the heat created passing off with sufficient rapidity to prevent firing. Fine coal should be invariably stored by itself and in such a way as to exclude as far as possible the air from entering the pile.

Slack coal has been stored successfully to a height of 8 or 10 feet by packing it as hard as possible, covering the surface with the finer portion in such manner as to as nearly as possible exclude air and water.

Water entering the bottom of a storage pile is exceedingly dangerous from a firing standpoint.

Method of Unloading

(1) No plan covering the unloading of storage coal should be put into effect without due consideration to the work of reloading same, bearing in mind that in the event of spontaneous combustion the portion firing must be removed quickly.

Where locomotive cranes with clam-shell buckets are available, two parallel tracks, located at from 16 to 20 feet centers, should be laid down on high level ground cleared of all refuse and combustible matter. The loaded cars are placed on one track and unloaded by a crane operating on the parallel track, the coal being placed in a pile alongside the crane. The position of the cars and crane is reversed with the completion of the first pile. The width of the pile depends on the radius of the boom travel, and its maximum height is determined by the width of the base and the flow line of the coal, not exceeding, however, a total of 20 feet. The height should be decreased in the case of coals that have been known to fire easily. The tracks should remain in position for the quick removal of coal that may become overheated and for the subsequent reloading of the coal stored.

(2) Extensive investigation has shown that many fires have occurred in storage piles where a separation of the coarse and fine coal was made, by dumping the coal as unloaded, on the same spot, or along the center line of the pile, the coarse coal rolling down to the side, the fine coal accumulating at the center or axis of the pile; the air entering the pile through the coarser portion and acting on the centrally located mass of fine coal producing heat, which, on account of an insufficient air circulation, is not carried off with sufficient rapidity to prevent high temperatures and spontaneous combustion. This hazard will be very materially lessened if the clam-shell is lowered to a point just above the surface of the pile before the contents are dumped. A layer of coal 2 feet in height should be laid down to the full width of the base of the pile and over the entire length of same, the second and succeeding layers, each 2 feet in thickness, to be laid down in like

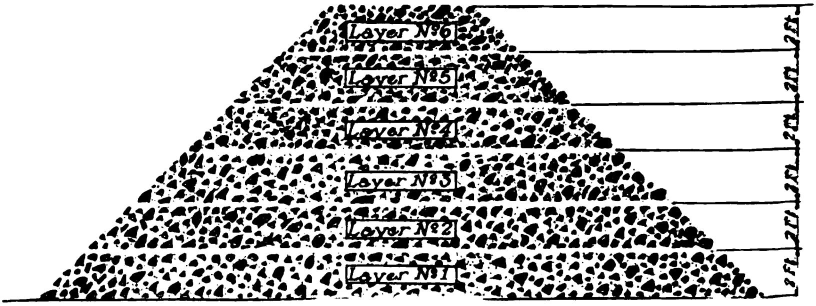


FIG. 74. METHOD OF BUILDING PYRAMIDAL PILE IN LAYERS*

manner. This method of unloading will eliminate the accumulation of broken fine particles in the center of the pile, and in addition, give the coal a limited opportunity to season before being covered up by the succeeding layer. A sketch showing a cross section of a pile so laid down is shown herewith.

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* Level of storage pile raised two feet at a time the full length of pile, by lowering the clam-shell to a point just above the surface of the pile before discharging contents.

(3) Where locomotive cranes are not available, coal from necessity is frequently stored by unloading self-clearing cars placed on a track on the top of the pile, the track raised from time to time on the coal. This arrangement has the disadvantage of causing an accumulation of crushed coal in the center of the pile, with lumps on the outside as referred to in paragraph (2). Where it is necessary to employ this method of unloading and after the pile is completed, the track should be moved from the top of the pile to the surface level and parallel to the storage pile, thus making provision for the quick removal of any portion that may fire by using the standard railroad non-revolving steam shovel, the American type railroad ditcher, or locomotive crane, for reloading the coal either in case of emergency heating or for current use. Coal so stored should not be piled to a height exceeding 12 to 15 feet, and the reloading tracks should be maintained readily accessible for prompt use in event of spontaneous firing, and the shovel, crane, or ditcher kept readily accessible and always in condition to be used.

Where mechanical means are employed for spreading coal so unloaded, a standard railroad ballast spreader is preferable to the track tie dragged through the coal underneath a car truck as commonly done.

(4) Trestle storage should be restricted to the handling of coal of established reputation for safe-keeping. The fire hazard attendant on placing storage coal around the wooden trestle, plus the cost of construction of same, and the difficulty of handling, makes this method of storage inadvisable.

(5) Any attempt toward the storage of coal will prove, at best, only partially successful, unless some one responsible individual is placed in charge of same with full authority to co-ordinate the various branches of the purchasing and operating departments. A thoroughly competent foreman should be maintained at every storage pile to oversee the storage, to inspect the billing before cars are unloaded, to determine the source of supply and the grade of coal furnished, and to divert to current consumption cars received of grade or kind other than that prescribed.

(6) After the work of storage is completed the storage piles should be adequately policed to prevent wholesale loss by theft and to insure the detection of excessive temperature. It is generally agreed that any method of ventilating stock piles heretofore employed is insufficient to safeguard them. Excessive heating is easily detected by a careful examination of the pile, using the sense of smell; and in addition the inspector should be equipped with a few sharpened steel rods, which should be driven into the pile at frequent intervals. Any excess heat generated may be detected by feeling the rod immediately upon its removal. If a hot spot is found with the rods, the temperature should be carefully watched with a thermometer placed inside a pipe driven into the pile at the hot place.

(7) All coal stored should be picked up and consumed under an established schedule and during the period of car and coal shortage, when transportation is most expensive and the facilities of the carrier are in maximum demand.

EUGENE MCAULIFFE,
Manager Fuel Conservation Section.

APPENDIX III

SPACE OCCUPIED BY COAL

The question is frequently asked: "How many cubic feet are there in a ton of coal, or how many tons of coal will a railroad car, bin, etc., of a given size hold?"

Knowing the specific gravity of any coal, the weight of a solid cubic foot can be readily computed. While such values are useful in computing the tonnage of coal in the ground, they are not useful in determining the weight per cubic foot of coal broken into commercial sizes to be used for fuel or for storage. The weight of coal in commercial sizes depends upon the specific gravity, size, and condition of the coal, and the extent to which it has been shaken down or settled.

The following is a summary of the information available, compiled from the literature on the subject and from replies to a questionnaire sent to about seventy manufacturers of coal handling machinery, to engineers, and to various users of coal.

A tabulation of the weight of 177 samples of coal from many parts of the United States will be found in Technical Paper No. 184 of the United States Bureau of Mines. These tests were made on domestic sizes of coal received in barrels. The coal was shoveled loosely into a box measuring 2 ft. by 2 ft. by 2 ft. and leveled off with a straight edge. The results show a variation in bituminous coal from the several coal districts of the United States as follows:

TABLE 18

WEIGHT OF BITUMINOUS COAL IN POUNDS PER CUBIC FOOT BY DISTRICTS

REGION	WEIGHT IN LB. PER CU. FT.
Appalachian: Pa., W. Va., Md., Va., Ohio, Tenn., Ala., and Eastern Ky.	43 to 57.5
Eastern Interior Basin: Ill., Ind., and Western Ky.	44 to 55
Western Interior Basin	45.5 to 59
Rocky Mountain	44.5 to 52.5

An average of these same results by states is given in Table 19, but for exact information as to coal from any particular district and of any particular size, reference should be made to the original paper as the averages given include a variety of sizes.

TABLE 19

WEIGHT OF BITUMINOUS COAL IN POUNDS PER CUBIC FOOT BY STATES*

STATE	NUMBER OF SAMPLES	AVERAGE WEIGHT PER CUBIC FOOT	EXTREME VALUES PER CUBIC FOOT
Alabama	5	51.3	45.5–54.0
Arkansas	4	53.3	49.5–59.0
Illinois	14	48.8	45.0–55.5
Indiana	9	46.1	44.0–49.0
Iowa	2	47.0	46.5–47.5
Kansas	2	52.8	50.0–55.5
Kentucky	11	47.2	43.0–54.5
Montana	2	52.3	52.0–52.5
Ohio	4	47.3	46.0–49.0
Oklahoma	4	48.5	45.5–50.0
Pennsylvania	41	51.2	46.5–55.0
Tennessee	9	57.3	45.0–51.0
West Virginia	9	53.3	41.0–57.5
Wyoming	4	48.9	45.5–52.5

*United States Bureau of Mines.

The conclusions reached by the author of the paper are:

"A study of the foregoing table indicates that heavier weights may be expected for coals of high fixed carbon content than for those of low. Increased ash content seems to lower the unit weight. It is also true, in general, that the coals high in moisture are lighter than those low in moisture and the younger coals are lighter than the older coals.

"These variables combine in so many ways, however, that it is difficult to determine from the data available anything more than a general trend and consequently little use can be made of the knowledge of a change of one or more of the variables."

The change in weight due to wetting and shaking down a sample are summarized in the same paper as follows:

"1. Of two samples of any coal that are composed of the same proportions of pieces of different sizes, the sample having the higher moisture content will usually weigh the more per cubic foot.

"2. A sample of higher moisture content will usually occupy more space for the same number of pounds of (dry) coal than will a sample of lower moisture content. However, the increase in volume for the wet coal is not as great proportionately as is the increase in weight per cubic foot.

"3. Coal shoveled loosely into a container will settle appreciably if the container is shaken, and the weight per cubic foot will be correspondingly increased.

"4. Slack coal composed of a mixture of the smaller pieces up to and including nut size weighs more than screened nut coal.

"This last statement coincides with the conclusions drawn from experiments with concrete mixtures, which have shown that a much denser mixture can be made by using certain proportions of various sized pieces. Pieces of nearly uniform size when piled leave about 45 per cent of voids. If these spaces are filled

with still finer coal of uniform size the weight of the mass is increased and the interstices in the finer coal can again be filled with still finer pieces, resulting finally in a dense mass. It is evident, therefore, that the relative proportions of fine and coarse material have a considerable influence on the weight per cubic foot of the mass."

Table 20 contains the results of a questionnaire which was sent to a number of coal handling machinery manufacturers, engineers, and coal users for the purpose of obtaining current practice upon the subject. It must be remembered in this connection, however, that these figures do not represent generally figures based upon tests of actual conditions but rather upon current practice, allowing an ample factor of safety, as most manufacturers desire to give the customer ample capacity so that they may be on the safe side in calculating tonnage or space.

TABLE 20

WEIGHT PER CUBIC FOOT OF COAL AS GIVEN BY MANUFACTURERS

COMPANY	Kind and Size of Coal	Cu. Ft. per Ton*	Wt. per Cu. Ft. in Lbs.	Angle of Repose in Degrees	REMARKS
Harriman, F., Mach. Co....	....	37	....	....	Mine car design.
Hyatt Roller Bearing Co...	Bituminous.	....	52½	....	"
Sanford Day Iron Works...	Bituminous Mine-run.	40	....	....	"
Hockensmith Wheel & Mine Car Co.	Bituminous Mine-run.	....	50	....	"
Atlas Car & Mfg. Co.......	Bituminous Mine-run.	40	....	40–45	"
	Anthracite.			30–33	
Cherry Tree Mach. Co.....	....	37½	....	....	"
Lakewood Engineering Co..	Loose Bituminous.	....	50	30	Mine and industrial car design.
	Anthracite.	....	54–56	30	
Helmick, F., Mach. Co.....	....	42	....	Varied with coal	Gross ton. Mine car design.
Jeffrey Mfg. Co............	Pocahontas.	40	50	35–37½	Practice in building chutes.
	Pittsburgh Bituminous.			40	" " " "
	Ind. and Ill.			40	" " " "
	Anthracite.			30	" " " "
	Bituminous.			40	Open piles.
	Anthracite.			37½	" "
Roberts & Schaefer Co.....	Bituminous Mine-run.	....	50	....	....
	Anthracite.	....	57	30–35	
	Lignite.	....	45		
	Bituminous.			35–40	
Western Wheeled Scraper Co....................	Bituminous Slack.	45	....	45	Ton of 2240 lb.

*2000 pounds.

TABLE 20—Continued

COMPANY	Kind and Size of Coal	Cu. Ft. per Ton*	Wt. per Cu. Ft. in Lbs.	Angle of Repose in Degrees	REMARKS
Robins Conveying Belt Co.	1¼ in.-¾ in. Nut.	38½	52		Loose.
	“	35½	56		Well shaken down.
Wood Equipment Co.	Mine-run to Lump.	35–45			
	Large Lump.	55			
	Wet mine-run	30			
United Iron Works Co.		48		1½–1	Kansas Mine-run.
Bucyrus Co.		40½		50	1½ cu. yd. per ton excavating machinery
Barber-Greene Co.		40		45	
Macdonald Engineering Co.		45	45	38	Practice.
			40	45	Average as noted.
Brown Hoisting Mach. Co.	Bituminous.	40		1½ hor. to 1 ver.	
	Anthracite.	35			
Wellman-Seaver-Morgan Co.	Bituminous.	40			
	Bituminous Mine-run.			43–45	
R. H. Beaumont Co.	Bituminous.	40	50	Max. Min.	
	Bituminous Mine-run.			45 35	
	Crushed Bituminous.			45 35	
	Anthracite.			30 27	
	Coke.			50 40	
McMyler-Interstate Co.	Bituminous.		50	45	
	Anthracite.		56	30	
Webster Mfg. Co.	Bituminous.	40		35	
	Anthracite.			27	
Morrow Mfg. Co.			50		Bin design.
Great Lakes Dredge and Dock Co.		40			Dock and bin design.
Jacobsen & Schraeder	Bituminous.		50	35	General practice.
	Anthracite.		52	27	“
	Coke.		30	35–45	“
	Bituminous.		50–55		More exact practice.
	Anthracite.		52–55		“
	Coke.		25–32		“
Watt Mining Car Wheel Co.		40			Mine car design.
Heyl & Patterson Inc.	Bituminous.	40		40	
	Anthracite.	36		30	
Link-Belt Co.	Bituminous Mine-run, Lump, Egg, and Nut.	40		40	Design for bins and storage. This has been found to give ample capacity under approximately the extreme conditions.
	Bituminous ⅜ in. and under.	45		40	
	Anthracite.	37		27	
Phillips Mine and Mill Supply Co.	Bituminous Mine-run.		52	45	Mine car and small storage bin design

*2000 pounds.

The Peabody Coal Company uses the following figures in estimating storage for coal and coke in coal yard:

TABLE 21

CUBIC FEET PER TON OF COAL*

BITUMINOUS	CUBIC FEET PER TON	ANTHRACITE	CUBIC FEET PER TON
Pocahontas Lump and Egg	35.5	Chestnut	34
Pocahontas Mine-Run and Nut	36..	Range	35
Pocahontas Slack	35.	Small Egg	35
Hocking	41.	Large Egg	36
Screenings	40.	Pea	33
Indiana Lump	41.	Buckwheat	32
Mine-Run	36.	Dust	35
Smithing	43.		
Quaker Egg and Nut	40.	COKE	
Quaker Lump	38.	Petroleum	72
Acorn Lump	40.	Gas House	66
New Era	38.	Solvay Nut	55
No. 3 Washed Nut	42.		
Wasco Lump	40.		

*Peabody Coal Company.

Mr. J. A. Garcia of the Allen and Garcia Company, Chicago, has furnished the following results of actual tests on a large number of cars of coal loaded by the Dering Coal Company in 1907. The volume was calculated from measurements made on railroad carloads just after they left the mine tipple. The results are shown in Table 22. The work was scattered over a period of several months and the data were collected by three different division engineers acting under definite instructions from Mr. Garcia.

TABLE 22

WEIGHT PER CUBIC FOOT OF ILLINOIS AND INDIANA COAL†

COMPANY DERING COAL CO.	Cu. Ft. per Ton‡	Wt. per Cu. Ft.	Kind and Size of Coal	Specific Gravity	REMARKS
West Frankfort, Franklin County, Ill.			Vein 6	1.310	
	34.8	57.4	Mine-run		
	34.3	58.3	Mine-run		
	37.0	54.1	1½ in. (round) Screenings		
	40.8	48.9	1½ in. to 3 in. Nut		
	41.2	48.5	3 in. to 6 in. Egg		
	40.0	50.0	6 in. Lump		
			Vein 6		
Montgomery County, Ind., Vein 6	37.5	53.2	Mine-run	1.339	
	38.1	52.5	⅞ in. bar (Screenings)		
	40.5	49.4	6 in. (round) Screenings		
	38.6	51.8	1¼-3 in. Nut		
	41.8	47.8	6 in. Lump		
	42.1	47.5	1¼ in. Lump		
	40.1	49.8	⅞ in. (bar)		

†Estimates of Mr. J. A. Garcia.
‡2000 pounds

TABLE 22—Continued

COMPANY DEERING COAL CO.	Cu. Ft. per Ton*	Wt. per Cu. Ft.	Kind and Size of Coal	Specific Gravity	REMARKS
			Vein 6	1.305	
Vermilion County, Ill.	40.5	49.3	Mine-run		
	45.2	44.1	1¼ in. (bar) Screenings		
	45.1	44.3	⅞ in. (round) Screenings		
	50.2	39.8	⅞-2 in. Nut		
	47.8	41.8	2 in. (round) Lump		
	43.8	45.6	1¼ in. (bar) Lump		
			Vein 3	1.372	
Vermilion County, Ind.	36.7	54.4	Mine-run		
	40.0	49.0	1¼ in. (bar) Lump		
			Vein 4	1.241	
Vermilion County, Ind.	38.1	52.5	Mine-run		
	40.8	49.0	1¼ in. (bar) Screenings		
	45.0	44.4	2½ to 4 in. Egg		
	42.6	46.9	4 in. Lump		
	43.5	45.9	1¼ in. (bar) Lump		
			Vein 5	1.368	
Vermilion County, Ind. and Sullivan County, Ind.	37.2	53.7	Mine-run		
	39.3	50.9	Mine-run		
	38.3	52.2	1¼ in. (bar) Screenings		
	40.6	49.2	1½ in. (bar) Lump		
	39.9	50.0	1¼ in. (bar) Lump		
			Vein 6		
Sullivan County, Ind.	40.7	49.1	1¼ in. (bar) Screenings		
	38.3	52.2	1¼ in. (bar) Screenings		
	41.0	48.7	1½ in. (round) Screenings		
	37.7	52.9	1 in. (round) Screenings		
	42.8	46.7	1¼-2½ in. Nut		
	42.8	46.7	1-2¼ in. Nut		
	41.3	48.3	2½-4 in. Egg		
	45.3	44.1	1½-4 in. Egg		
	40.1	49.8	2½-4 in. Egg		
	42.3	47.2	1¼ in. (bar) Lump		
	38.8	51.5	4 in. Lump		
	42.8	46.7	4 in. Lump		
	38.4	52.0	4 in. Lump		
	42.5	47.0	1½ in. Lump		

*2000 pounds.

Tables 23 and 24 give other results for bituminous coal and Table 25 gives results for anthracite coal.

TABLE 23

SPACE OCCUPIED BY BITUMINOUS COAL IN CUBIC FEET PER TON†

KINDS	CUBIC FEET PER TON‡
Cumberland	36.65
Clearfield	33.55
New River	40.15
Pocahontas	34.00
American Cannel	41.50
English Cannel	42.30

†Mines and Minerals, Nov., 1907.

‡2000 pounds.

TABLE 24

SPACE OCCUPIED BY BITUMINOUS COAL IN CUBIC FEET PER TON*

Kind	Cubic Feet per Ton†	Kind	Cubic Feet per Ton†
Pittsburgh	48.2	Cumberland, Max.	42.3
Erie	46.6	Cumberland, Min.	41.2
Hocking Valley	45.4	Blossburg, Pa.	42.2
Ohio Cannel	45.5	Clover Hill, Va.	49.0
Indiana Block	51.1	Richmond, Va. (Midlothian)	41.0
Illinois	47.4	Cannelton, Ind.	47.0
Pittsburgh	47.1	Pictou, N. S.	45.0
		Sydney, Cape Breton	47.0

*Trautwine's Engineer's Pocket Book.

†2240 pounds.

TABLE 25

SPACE OCCUPIED BY ANTHRACITE COAL IN CUBIC FEET PER TON‡

Kinds	Cubic Feet per Ton¶				
	Broken	Egg	Stove	Chestnut	Pea
Lackawanna	37.10	36.65	34.90	34.35	37.25
Garfield Red Ash	37.30	36.95	36.35	36.35	37.50
Lykens Valley	37.55	37.25	37.55	37.25	38.50
Shamokin	38.05	37.70	37.25	37.25	38.50
Plymouth Red Ash	34.90	34.85	34.75	34.70	36.90
Wilkes-Barre	34.95	34.35	33.75	34.00	36.90
Lehigh	33.30	33.80	33.55	32.55	33.05
Lorberry	34.65	34.20	33.80	33.55	35.20
Scranton	35.35	35.20	34.60	33.30	34.95
Pittston	35.45	34.95	34.35	33.70	35.50

‡Mines and Minerals.

¶2000 pounds.

The following formulas from which Table 26 was calculated are given in General Catalog 18 of the Gifford-Wood Company of New York (See Fig. 75).

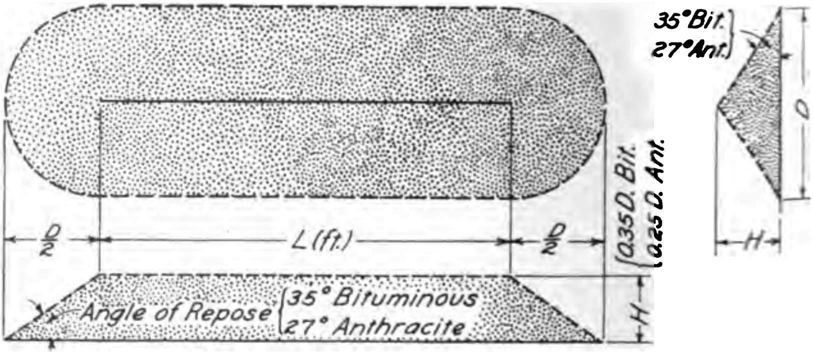

FIG. 75. DIMENSIONS FOR DETERMINING VOLUME AND WEIGHT OF COAL PILES

Formulas

For Bituminous Coal:

Vol. of each conical end $= 0.045815D^3$; vol. of cone $= 0.09163D^3$.

Vol. per foot of straight portion $= 0.175D^2$.

For Anthracite Coal:

Vol. of each conical end $= 0.0327D^3$; vol. of cone $= 0.0654D^3$.

Vol. per foot of straight portion $= 0.125D^2$.

Tons = Vol. in cu. ft. ÷ cu. ft. per ton, from table below. 40 cu. ft. per ton was used in calculating the following table.

TABLE 26
VOLUME AND TONNAGE OF BITUMINOUS COAL PILES

D Feet	Vol. in Cubic Feet		Short Tons	
	Conical Ends, Each	Per Ft. of Straight Portion	Conical Ends, Each	Per Ft. of Straight Portion
10	45.82	17.50	1.15	0.44
11	60.90	21.20	1.52	0.53
12	79.00	25.20	1.97	0.63
13	100.50	29.55	2.51	0.74
14	125.75	34.30	3.14	0.86
15	154.30	39.40	3.86	0.98
16	187.30	44.80	4.68	1.12
17	225.00	50.60	5.63	1.26
18	267.00	56.70	6.67	1.42
19	314.00	63.20	7.85	1.58
20	402.50	70.00	10.05	1.75
25	715.00	109.30	17.88	2.74
30	1236.00	157.50	30.85	3.94
35	1965.00	214.50	49.10	5.36
40	2930.00	280.00	73.20	6.99
45	4170.00	354.50	104.10	8.86
50	5720.00	437.50	143.00	10.93
55	7620.00	529.00	190.50	13.22
60	9900.00	630.00	247.50	15.76
65	12600.00	738.00	315.00	18.43
70	15700.00	857.00	392.00	21.40
75	19320.00	984.50	483.00	24.60
80	23450.00	1120.00	586.00	28.00
85	28100.00	1265.00	702.50	31.60
90	33400.00	1420.00	835.00	35.50
95	39250.00	1580.00	980.00	39.50
100	45815.00	1750.00	1145.00	43.75

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EMISSIVITY OF HEAT FROM VARIOUS SURFACES

BY

V. S. DAY

RECEIVED
JUL 1920

[THIS BULLETIN IS THE SECOND OF A SERIES ON WARM-AIR FURNACE RESEARCH]

BULLETIN No. 117

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BULLETIN NO. 117 JANUARY, 1920

EMISSIVITY OF HEAT FROM VARIOUS SURFACES
WITH SPECIAL REFERENCE TO
WARM-AIR FURNACE INSTALLATIONS

RESULTS OF COMPARATIVE TESTS ON
COVERED AND UNCOVERED SHEET METAL SURFACES
MADE IN CONNECTION WITH THE
WARM-AIR FURNACE INVESTIGATION

CONDUCTED BY
THE ENGINEERING EXPERIMENT STATION
UNIVERSITY OF ILLINOIS
IN COÖPERATION WITH
THE
NATIONAL WARM-AIR HEATING AND VENTILATING
ASSOCIATION

BY
V. S. DAY
RESEARCH ASSISTANT, ENGINEERING EXPERIMENT STATION

ENGINEERING EXPERIMENT STATION
PUBLISHED BY THE UNIVERSITY OF ILLINOIS, URBANA

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EMISSIVITY OF HEAT FROM VARIOUS SURFACES

I. INTRODUCTION

1. *Preliminary Statement.*—The work reported upon in this bulletin was done in connection with the Warm-Air Furnace Investigation now in progress at the University of Illinois. This investigation has for its object the determination of the efficiencies and capacities of warm-air furnaces and a study of the proper conditions of installation and operation, so that furnaces may be accurately rated and properly selected for the requirements of actual service. The work is being conducted under a coöperative agreement between the National Warm-Air Heating and Ventilating Association and the Engineering Experiment Station of the University of Illinois. This bulletin is a report of the tests of heat insulating materials and surfaces made as a part of the Investigation, and is included in item (4) of the Objects of the Investigation.*

2. *Previous Investigations.*—In May 1919, it was observed in these tests that greater temperature reduction occurred in air passing through bright tin pipes covered with asbestos paper, such as are commonly used in furnace heating, than occurred in air passing through the same bright tin pipes uncovered, all other conditions in the comparative tests being the same. It was therefore evident that the actual heat loss was greater through the asbestos paper-covered pipes than through the same pipes uncovered.

This fact was reported at the annual Spring Meeting of the National Warm-Air Heating and Ventilating Association, Columbus, Ohio, June 11, 1919, as follows: " . . We found that we lost about 35 per cent more heat through the pipe covered with asbestos paper than through the same tin pipe not covered. . . This great loss amounts to approximately 5 per cent of the coal consumed. . . Furthermore, it costs from ten to fifteen dollars to cover the heat pipes of the average house installation with asbestos paper."†

---

* University of Illinois Engineering Experiment Station, Bulletin No. 112, "A Report of Progress in Warm-Air Furnace Research," by Prof. A. C. Willard, p. 8.

† Proceedings of the National Warm-Air Heating and Ventilating Association, p. 70. June 11, 1919.

Because of the inefficacy of many of the present warm-air furnace heat insulating methods, it is evident that a complete study of various insulating materials, coverings, and surfaces would be justified.

3. *Acknowledgments.*—Credit is due Professor A. C. WILLARD for the original idea of the scheme for testing the samples, and for the keen support which, as the active supervisor of the Investigation, he gave this work.

Professor A. P. KRATZ gave valuable advice and assistance in the use of the thermocouples.

4. *Significant Conclusions.*—The results of the tests have been given some publicity heretofore, but not in the complete form presented in this bulletin. The following significant results as applied to warm-air furnace heating are deserving of special emphasis.

(1) The use of thin sheets of asbestos paper on bright tin heat pipes results in a waste of heat. The use should be abandoned.

(2) Uncovered bright tin pipes are more efficient carriers of heated air than asbestos paper-covered bright tin pipes. See item (4).

(3) This fact is true regardless of the degree of brightness of the tin surface.

(4) No small number of applications of asbestos paper will suffice as an insulator. Several thicknesses are necessary to make a covering equal in this respect to the bare tin.

(5) The accumulation of dust and dirt on the pipes does not greatly alter the amount of the loss.

(6) The heat loss from warm-air furnace pipes covered with one layer of asbestos paper is a serious item in the cost of heating, amounting to more than 5 per cent of the coal consumption, depending upon the number and size of the pipes used.

(7) The fact that pipes are partly protected from convection currents of air by joists and studding does not greatly affect the loss.

(8) *Unless the insulation excels the uncovered bright tin in heat insulation properties it should not be used.*

(9) Such materials are available and the tests have shown their merits.

II. The Testing Equipment.

The report mentioned in paragraph 2, which was made at Columbus, Ohio, gave the results of tests on the Auxiliary Testing Plant (see Fig. 6).* It was difficult to obtain entirely satisfactory data on this plant because of the variation in the velocity of the air flowing up the leader and the difficulty of correctly measuring the temperature of the air, as described later in this bulletin. It was therefore decided that a special apparatus should be devised which would eliminate possible errors in temperature measurements.

5. *Description.*—The apparatus here described, (Figs. 1 and 2) was the one used in the tests reported in this bulletin. It consisted of low pressure steam heated drums, five in number, surrounding a central steam header from which the drums drew their supply of steam. The drums were accurately uniform in size, ten inches in diameter by twenty inches in length and were made of sheet metal of the kind to be tested. Steam was condensed in the drums by the cooling action of the air surrounding them and was discharged through water seals connected to each drum. These seals were U-tubes made of pipe, and were long enough to contain a water head of four feet. As the steam condensed the seals became filled with water; the condensate then dripped over into receivers as fast as it accumulated. The water in the seals cooled to room temperature before it dripped into the receivers so that evaporation was not influenced by the heat of the water in the receivers. Each receiver was mounted on a small weighing scales accurate to one one-hundredth pound.

A mercury manometer was used to obtain the pressure of the steam in the central header, and since the temperature of the steam for any known pressure may be taken directly from steam tables, it was possible to determine the temperature of the medium within the drum with great accuracy. A pressure regulator in the steam supply line held the pressure constant within a small fraction of a pound, about 0.2 pound being the variation during a test; as the temperature change for the pressure variation was negligible, the temperatures were uniform and accurate within one degree.

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* University of Illinois Engineering Experiment Station, Bulletin No. 112, "A Report of Progress in Warm-Air Furnace Research," by Prof. A. C. Willard, pp. 45-49.

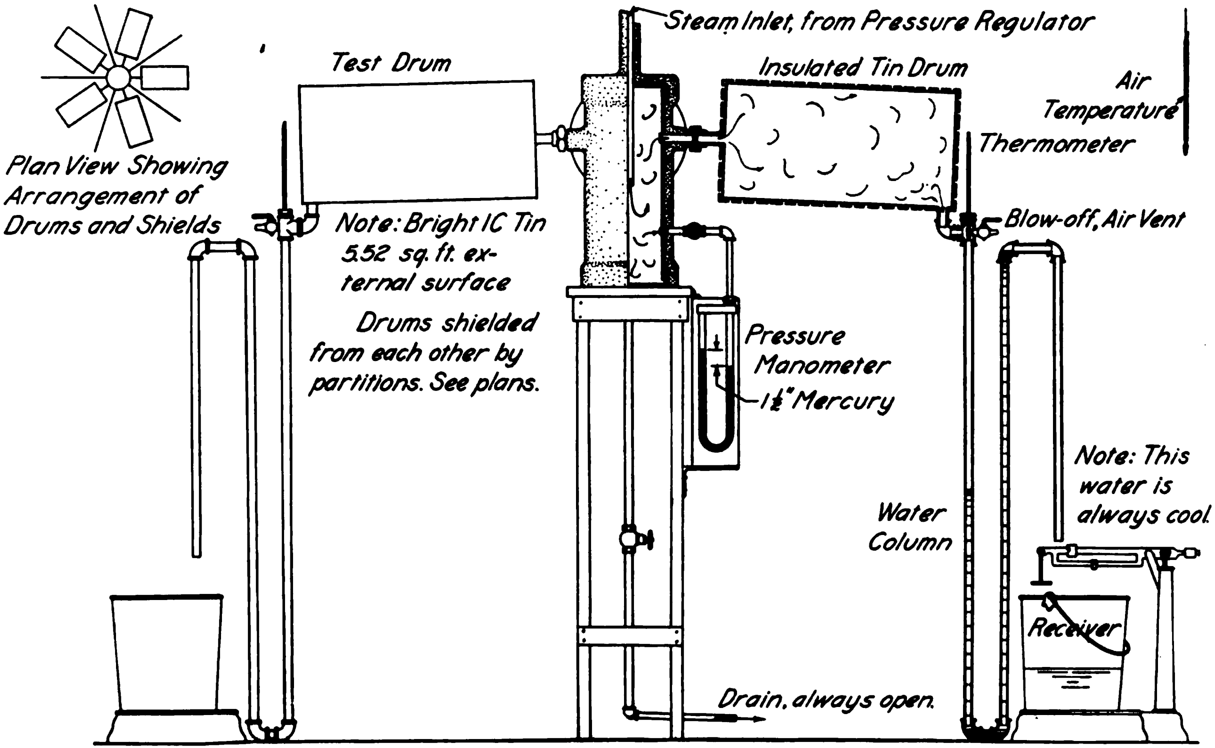

Plan View Showing Arrangement of Drums and Shields
Test Drum
Note: Bright IC Tin 5.52 sq. ft. external surface
Drums shielded from each other by partitions. See plans.
Steam Inlet, from Pressure Regulator
Insulated Tin Drum
Air Temperature Thermometer
Blow-off, Air Vent
Pressure Manometer
1½" Mercury
Note: This water is always cool
Water Column
Receiver
Drain, always open.

FIG. 1. SECTIONAL ELEVATION OF STEAM DRUM PLANT FOR TESTING SURFACES FOR HEAT EMISSIVITY

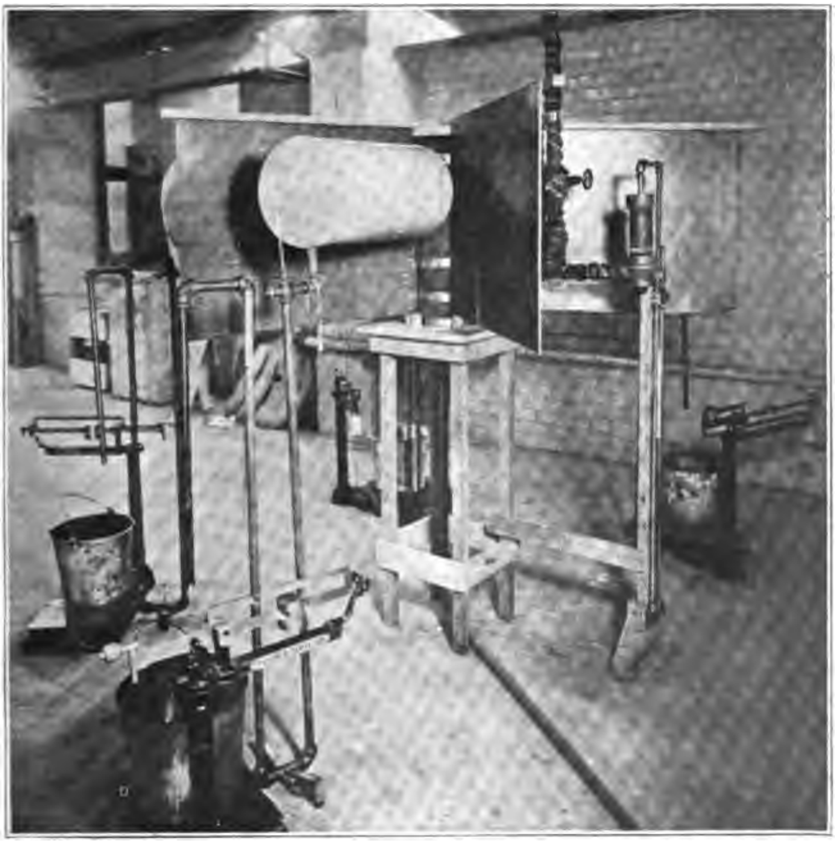


FIG. 2. PHOTOGRAPH SHOWING THE PRINCIPAL OPERATIVE FEATURES OF THE STEAM DRUM PLANT

No thermometers were required for determining the steam temperature, but one was used in each drum at the point of outlet of the condensate to detect the presence of air in the drums. The readings of these thermometers decreased upon the formation of air pockets in the lower part of the drums or in the connected piping. Air could be blown out of small petcocks located near the thermometers in the piping. No effects on the coefficients were noticeable when steam was allowed to escape for short periods from these petcocks, which could therefore be opened during a test to discharge any small accumulation of air.

The drums were shielded from radiation from each other by blackened compo-board partitions. These partitions did not in any way interfere with the flow of natural air currents. The temperature of the air was measured by thermometers suspended at the elevation of the drums at convenient positions nearby. The thermometers were not affected by radiation from the drums.

Thus, the actual measurements involved were simple and were not liable to serious error. These measurements consisted of the weighing of the steam condensed, the reading of the pressure of the steam, and the reading of the room air temperature.

III. The Tests

6. *Operation.*—The tests reported herein, forty in number, with four drums under steam in each test, were carried out at night when the doors and windows of the large laboratory were closed. No air currents were noticeable near the apparatus. A period of ten hours was chosen for the duration of a test as that time was sufficient to permit accumulations of condensate great enough to render negligible the slight error in weighing. These quantities of water varied from 5 to 20 pounds depending upon the surface material of the test drums. The steam pressure was constant on any given test within 0.2 of an inch head of mercury. In all the tests there was only one case in which the thermometers indicated the presence of air in the drums at the end of ten hours operation. The greatest variation of temperature of the surrounding atmosphere during any night was four degrees Fahrenheit. A recording thermometer was used to show the uniformity of the laboratory temperature.

The drums were tested in different positions around the steam header in order to compensate for any irregularity in the flow of steam to the drums or in the currents of air about the drums. As no irregularities were noticeable in the values of the coefficients of emissivity for the various positions, the practice was abandoned after the first four drums were tested in the interchanged positions.

One drum, of bright tin not insulated, was in operation in all tests. Its performance served as an indication of any lack of uniformity in the conditions existing throughout the tests.

In order to make correction for the loss of water by evaporation from the receivers, a receiver of water was balanced on a scales and the loss in ten hours actually determined by weighing. After several trials in which the loss ranged from 0.10 to 0.12 pound it was decided to use the value 0.11 pound. This amount was applied as a correction to all the weights of water. Every test was repeated until the results obtained were found to agree within very small limits. In no case are the data reported, the result of less than two tests, and in most cases four were run. Two tests were considered sufficient if the results agreed within one per cent of their mean value.

7. *Specimens Tested.*—A complete list of the drums tested is given in Figs. 5 and 5*a*. In the list will be found a description of the insulation or the surface material, the actual area of the drum exposed to the steam, and an abstract number assigned to the drum (which will be useful in connecting the description with the results reported later in this paper). Fig. 4 shows sections through some of the insulations which were of complex construction.

IV. THE CALCULATIONS

In calculating the coefficients of emissivity for the various surfaces it was assumed that heat of the vapor was entirely given up, upon condensation, to the air through the walls of the containers and the connected piping. Tests on the low pressure steam-line supplying the drums show a steam quality of over 99 per cent. The expression for the coefficient is, therefore, calculated as follows:

$$K_1 = \frac{rW}{A\,(t_s - t_a)} \qquad \ldots\ldots\ldots \quad (1)$$

in which, K_1 = B. t. u. per sq. ft. per hr. per 1 degree F.
r = latent heat of one lb. of the steam.
W = weight of condensate per hour.
t_s = temperature of the steam.
t_a = temperature of the surrounding air.
A = area of the drum exposed to the steam.

Correction must be made for the loss of heat through the half-inch pipe of which the water seal was made. This loss is not accounted for in the calculation for K_1 above. Three lineal feet of the half-inch pipe were exposed to the steam. The correction is made by using a coefficient of emissivity for this pipe of 2.50 B. t. u. per sq. ft. per hr. per 1 degree F. and the exposed area of 0.375 sq. ft., or, 2.50x0.375 = approximately 1.00 B. t. u. per hr. per 1 degree F. to be subtracted from the heat loss, or,

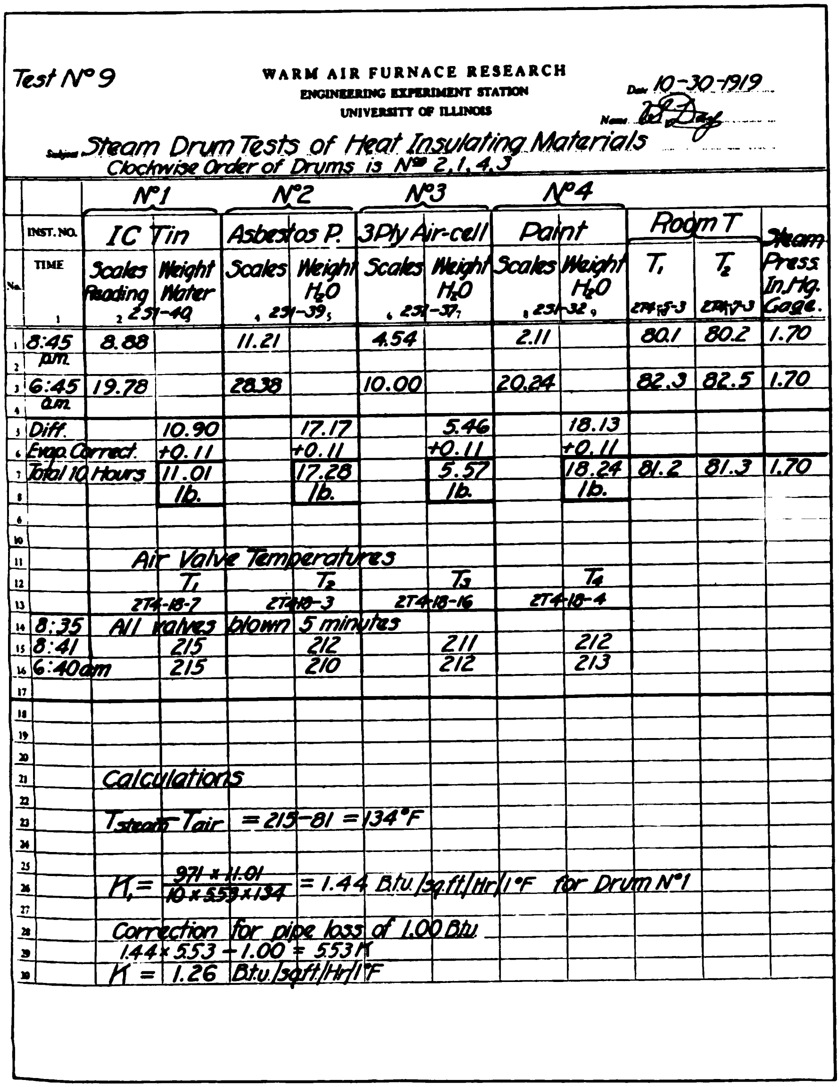
$$AK_1\,(t_s - t_a) - 1.00\,(t_s - t_a) = AK\,(t_s - t_a)$$

and

$$K \text{ corrected} = \frac{AK_1 - 1.00}{A} \qquad \ldots\ldots\ldots \quad (2)$$

This correction was verified by tests made on the drums with the water seals heavily insulated with hair felt. The values of K so determined agree closely with the values obtained by applying the correction.

Fig. 3 is a copy of a test data sheet and shows all readings and calculations for one test.



Test N° 9

WARM AIR FURNACE RESEARCH
ENGINEERING EXPERIMENT STATION
UNIVERSITY OF ILLINOIS

Date 10-30-1919

Name W. Day

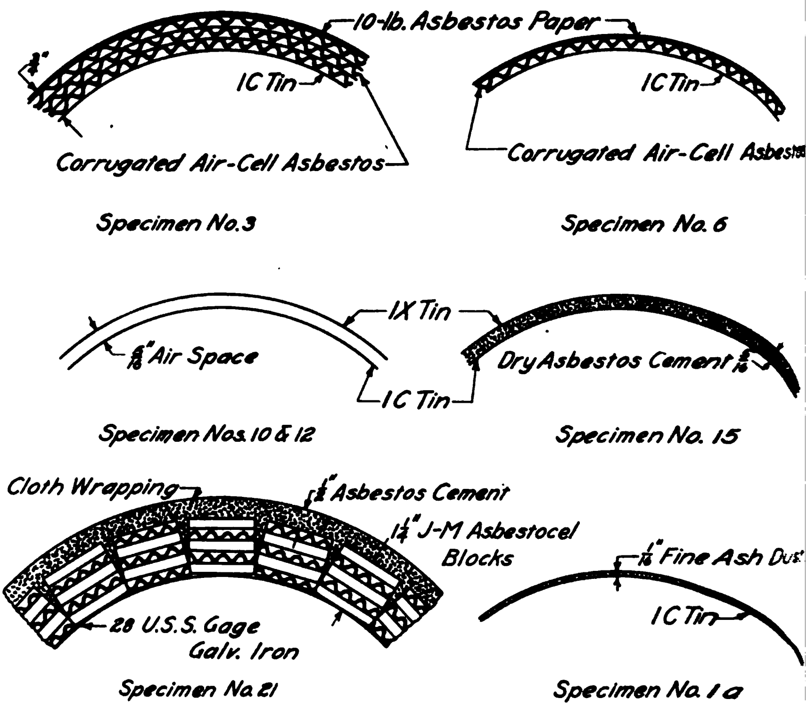
Subject Steam Drum Tests of Heat Insulating Materials
Clockwise Order of Drums is Nos 2, 1, 4, 3

		N°1		N°2		N°3		N°4				
	INST. NO.	IC Tin		Asbestos P.		3 Ply Air-cell		Paint		Room T		
No.	TIME 1	Scales Reading 2	Weight Water 3	Scales 4	Weight H_2O 5	Scales 6	Weight H_2O 7	Scales 8	Weight H_2O 9	T_1	T_2	Steam Press. In Hg. Gage.
		251-40		251-39		251-37		251-32		2T4-5-3	2T4-7-3	
1	8:45	8.88		11.21		4.54		2.11		80.1	80.2	1.70
2	pm.											
3	6:45	19.78		28.38		10.00		20.24		82.3	82.5	1.70
4	am.											
5	Diff.		10.90		17.17		5.46		18.13			
6	Evap. Correct.		+0.11		+0.11		+0.11		+0.11			
7	Total 10 Hours		11.01		17.28		5.57		18.24	81.2	81.3	1.70
8			lb.		lb.		lb.		lb.			
9												
10												
11		Air Valve Temperatures										
12			T_1		T_2		T_3		T_4			
13			2T4-18-7		2T4-18-3		2T4-18-16		2T4-18-4			
14	8:35	All valves blown 5 minutes										
15	8:41		215		212		211		212			
16	6:40 am		215		210		212		213			
17												
18												
19												
20												
21		Calculations										
22												
23		$T_{steam} - T_{air} = 215 - 81 = 134°F$										
24												
25												
26		$K_1 = \frac{971 \times 11.01}{10 \times 5.53 \times 134} = 1.44$ Btu./sq.ft./Hr./1°F for Drum N°1										
27												
28		Correction for pipe loss of 1.00 Btu.										
29		$1.44 \times 5.53 - 1.00 = 5.53 K$										
30		$K = 1.26$ Btu./sq.ft./Hr./1°F										

FIG. 3. A SAMPLE DATA SHEET FOR A TYPICAL TEST

V. Results of the Tests

8. *Discussion.*—The significance of the tests will be best understood by a study of the information presented in the diagrammatic chart, Figs. 5 and 5*a*. The heavy black bars afford a graphic comparison of the heat emitting value of the various surfaces. Reference must be made to the descriptive list of drums in order to connect the data with particular test specimens. The relative efficiencies of the various surfaces as heat insulators are given in the next to the last column of the chart. The coefficient for bright IC tin was used as the basis for this comparison.


10-lb. Asbestos Paper
1/4"
IC Tin
Corrugated Air-Cell Asbestos
IC Tin
Corrugated Air-Cell Asbes
IX Tin
3/16" Air Space
IC Tin
IC Tin
Dry Asbestos Cement 3/16"
Cloth Wrapping
1/2" Asbestos Cement
1 1/4" J-M Asbestocel Blocks
28 U.S.S. Gage Galv. Iron
1/16" Fine Ash Dus
IC Tin

Specimen No. 3
Specimen No. 6
Specimen Nos. 10 & 12
Specimen No. 15
Specimen No. 21
Specimen No. 1a

Fig. 4. Sections Showing Construction of Some of the Complex St
Coverings

The first result of importance is the convincing evidence which the tests present as an argument against the use of thin layers of asbestos paper covering on bright tin pipes. The heat loss was 39 per cent greater with one thickness of the paper than without. Such a loss is of no small degree of importance as calculations will show that it results in a waste of 5 per cent or more of the coal consumed in the average house furnace.

The fact that the heat loss from the warm-air pipes of a furnace system is of some consequence is not appreciated generally. A considerable part of the heat of the air flowing through the pipes of the average installation is dissipated from the pipe surface to the surrounding air and nearby objects. The insert in Fig. 6 sets forth the results of tests made to determine the amount of this loss. The tests were carried out on a single leader pipe furnace,* see Fig. 6, in which the quantity of air handled and the heat content of the same above the entering temperature could be readily ascertained. The heat loss was determined by calculation from the drop in temperature of the air in its passage through the pipe. The temperature and velocities indicated in the curves are fair representative values.

The significance of these preliminary tests is to bring out the fact that the heat loss from warm-air furnace pipes is a serious item. From the curves, it can be seen that in the case of the asbestos paper-covered pipes, the loss amounts to about 23 per cent of the heat of the air at the bonnet, above inlet air temperature. If the pipe is of bright tin and not covered, this loss is reduced to about 17 per cent of the heat available. In either case the loss is great; and with the further consideration that a warm-air furnace under average conditions of installation is, at best, only about 60 per cent efficient, it will be understood that the actual waste of coal ascribable to poor heat pipe insulation is enough to warrant attention.

The attempt was made in the steam drum tests to determine the effect upon the heat loss of having the drum partly enclosed so that free circulation of the air about the drum would be prevented. The experiment simulated the effect of running leader pipes between joists. The results of these tests as shown in No. 14 and No. 14*a* indicated a slight decrease in the value of K for the enclosed drum.

The argument has been advanced that if bright tin pipes were used without covering, they would soon become fouled with dirt and

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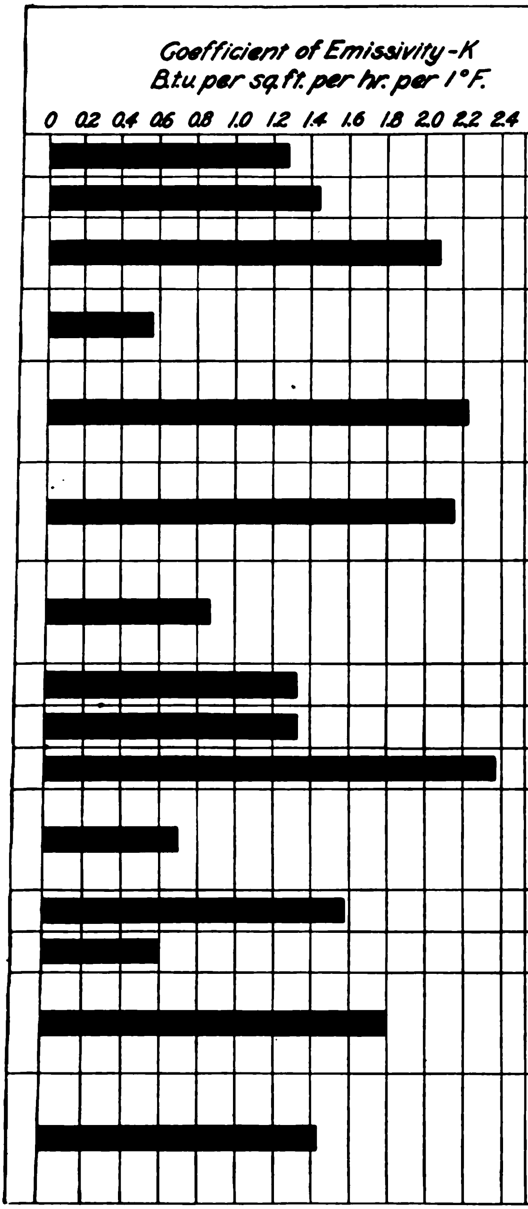
* University of Illinois Engineering Experiment Station Bulletin No. 112, "A Report of Progress in Warm-Air Furnace Research," by Prof. A. C. Willard.

Drum Number	Description of Surface	Area Exposed to Steam sq. ft.
1	1C tin, not insulated, bright	5.53
1a	Same as No. 1 with ash dust sifted on $\frac{1}{16}$" deep	5.53
2	1C tin with 1 thickness of 10-pound asbestos paper	5.52
3	1C tin with 3 thicknesses of air-cell asbestos and 1 thickness of 10-pound asbestos paper	5.50
4	1C tin with 2 applications of gray paint, (of zinc, linseed oil, and lithpone composition)	5.51
5	1C tin with 1 thickness of asbestos paper and 2 applications of paint, (No. 2 drum with same kind of paint as used on No. 4)	5.52
6	1C tin with 1 thickness of air-cell asbestos and 1 thickness of 10 pound asbestos paper, (No. 3 drum used)	5.50
7	1C tin nickel plated and polished	5.54
8	Galvanized iron, No. 28 U.S.S. gage	5.53
9	Black Iron, No. 28 U.S.S. gage, very rusty	5.52
10	Surface and drum No 3 with IX tin casing surrounding, with $\frac{5}{16}$" air-space and with 6 $\frac{1}{2}$" vent holes cut in the casing	5.50
11	1C tin (drum No. 1) coated with Bakelite lacquer	5.53
12	Same as No. 10 but with vents stopped	5.50
13	1C tin (drum No. 2) with 1 thickness of 10-pound asbestos paper and a surface of glaze finish printers' proofing paper	5.52
14	1C tin drum No. 4 with paint removed and a housing of compo-board construction, to represent joists, built around same. Housing 8" deep by 14" wide by 28" long	5.51

FIG. 5. DIAGRAMMATIC TABLE OF THE RESULTS OF

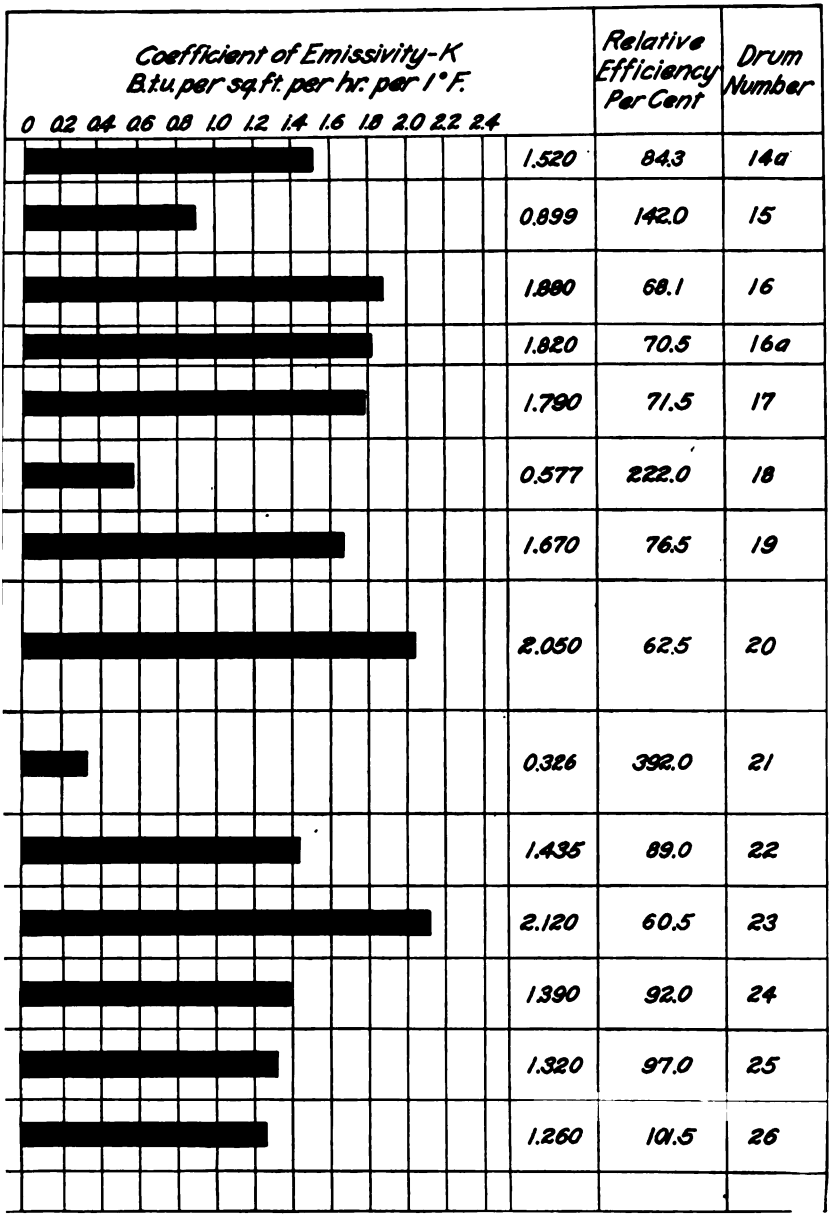


Coefficient of Emissivity - K B.t.u. per sq. ft. per hr. per 1° F.	Relative Efficiency Per Cent	Drum Number
1.280	100.0	1
1.440	89.0	1a
2.080	61.5	2
0.565	226.0	3
2.225	57.5	4
2.155	59.5	5
0.870	147.0	6
1.330	96.0	7
1.330	96.0	8
2.370	54.0	9
0.700	183.0	10
1.575	81.5	11
0.593	216.0	12
1.800	71.0	13
1.430	89.5	14

One Hundred Sixty Tests on Steam Drums

Drum Number	Description of Surface	Area Exposed to Steam sq.ft.
14a	Same as No. 14 with housing removed	5.51
15	Same as No. 10 but with the air-space packed with dry JM asbestos cement	5.50
16	IC tin with 2 thicknesses of 12-pound asbestos paper	5.52
16a	Same as No. 16 with ash dust sifted on $\frac{1}{16}$" deep	5.52
17	IC tin (drum No. 2) with 3 thicknesses of 12-pound asbestos paper	5.52
18	Galvanized iron (drum No. 8) with 3 thicknesses of air-cell asbestos and 1 of 12-pound paper	5.53
19	IC tin (drum No. 2) with 4 thicknesses of 12-pound asbestos paper	5.52
20	IC tin with 1 thickness of asbestos paper covered with a firm coating of white calcimine, (for determining the effect of light and dark surfaces)	5.51
21	Galvanized iron (drum No. 8) with $1\frac{1}{4}$" Asbesto-cel blocks covered with $\frac{1}{2}$" of asbestos cement and a cheesecloth wrapper	5.53
22	IC tin (drum No. 2) with 5 thicknesses of 12-pound asbestos paper	5.52
23	Same as drum No. 20 with lampblack calcimine on the surface used in that test	5.51
24	IC tin (drum No. 2) with 6 thicknesses of 12-pound asbestos paper	5.52
25	IC tin (drum No. 2) with 7 thicknesses of 12-pound asbestos paper	5.52
26	IC tin (drum No. 2) with 8 thicknesses of 12-pound asbestos paper	5.52

Fig. 5a. Continuation of the Diagrammatic Table of



Coefficient of Emissivity-K B.t.u. per sq. ft. per hr. per 1° F.	Relative Efficiency Per Cent	Drum Number
1.520	84.3	14a
0.899	142.0	15
1.880	68.1	16
1.820	70.5	16a
1.790	71.5	17
0.577	222.0	18
1.670	76.5	19
2.050	62.5	20
0.326	392.0	21
1.435	89.0	22
2.120	60.5	23
1.390	92.0	24
1.320	97.0	25
1.260	101.5	26

ESULTS OF ONE HUNDRED SIXTY TESTS ON STEAM DRUMS

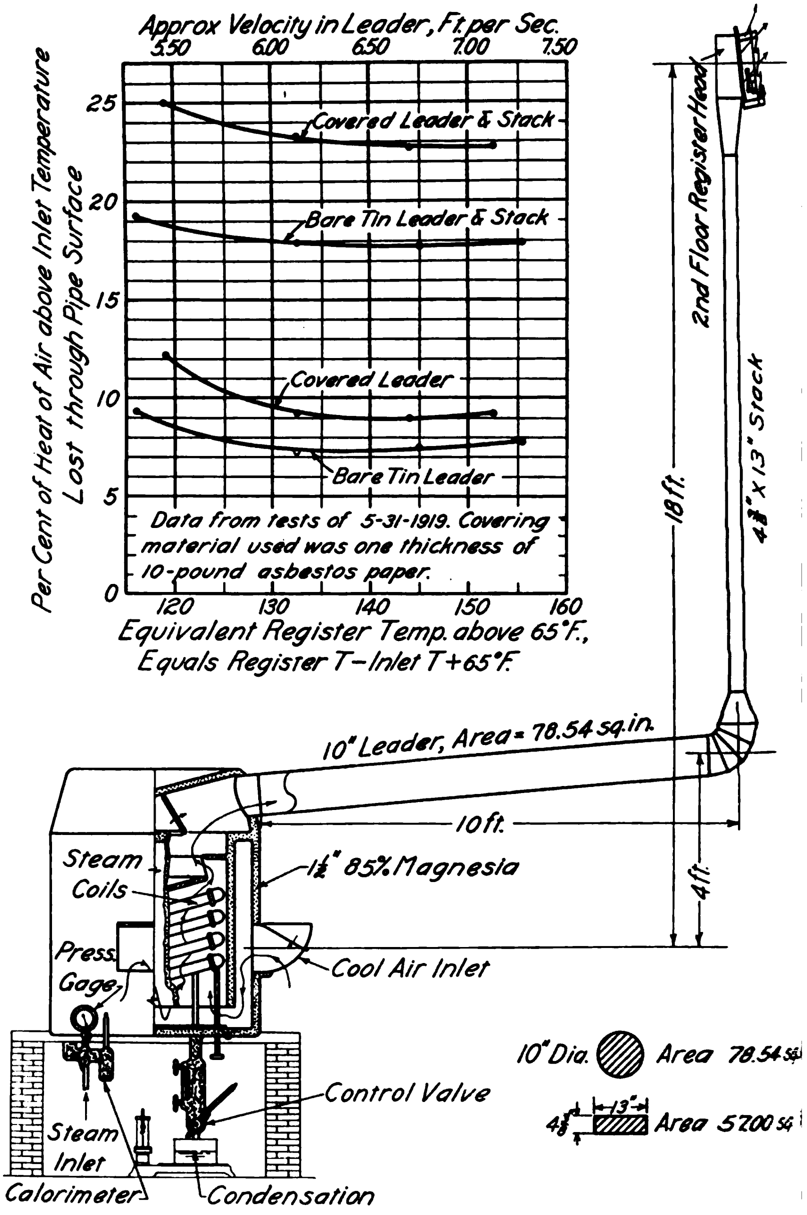

Approx Velocity in Leader, Ft per Sec.
5.50
6.00
6.50
7.00
7.50
Per Cent of Heat of Air above Inlet Temperature Lost through Pipe Surface
25
20
15
10
5
0
Covered Leader & Stack
Bare Tin Leader & Stack
Covered Leader
Bare Tin Leader
Data from tests of 5-31-1919. Covering material used was one thickness of 10-pound asbestos paper.
120
130
140
150
160
Equivalent Register Temp. above 65°F.,
Equals Register T - Inlet T + 65°F.
2nd Floor Register Head
4⅜" x 13" Stack
18 ft.
10" Leader, Area = 78.54 sq. in.
10 ft.
4 ft.
Steam
Coils
1½" 85% Magnesia
Press.
Gage
Cool Air Inlet
Control Valve
Steam
Inlet
Calorimeter
Condensation
10" Dia.
Area 78.54 sq
4⅜
13"
Area 57.00 sq

Fig. 6. Elevation of Auxiliary Furnace Plant with Insert Showi
Percentage of Heat Lost from Covered and from Bare Bright Tin Pi

dust and so rendered less efficient heat carriers than asbestos paper covered pipes. The fallacy of this argument is revealed by tests No. 1*a* and No. 16*a*. In these tests fine ash dust was sifted on the test drums, one of bare bright tin and the other asbestos paper covered. The dust was more than one-sixteenth inch deep on top of the drums. The results as shown in tests No. 1*a* and No. 16*a* of the chart indicate that the bare tin suffered a loss of 11 per cent in efficiency whereas the asbestos paper surface improved 2.4 per cent. There still remained, however, a difference of 25 per cent in favor of the bare tin pipe.

In order to demonstrate further the inefficacy of thin layers of asbestos paper as a heat insulator, tests were run in which the number of thicknesses of paper was increased until the heat loss became less than the loss through a bare bright tin specimen. The curve (Fig. 7) gives the results of these tests. Eight thicknesses of the twelve-pound paper were applied before the desired result was obtained. In these tests the moistened paper was wrapped tightly and shrunk on the drums so that only a small quantity of air was entrapped between the successive layers of paper. The total thickness of paper was two-

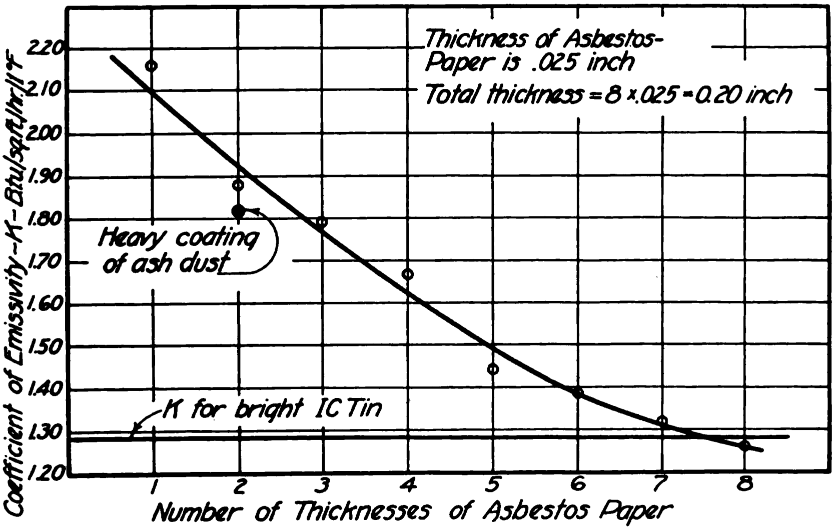


FIG. 7. CURVES SHOWING INEFFECTIVENESS OF COMMERCIAL ASBESTOS PAPER FOR INSULATION OF BRIGHT TIN PIPES

tenths of an inch. The impractical features of such a method of insulating are of course evident. The use of thin layers of asbestos paper on bright tin pipes must be abandoned if the best results are to be obtained in furnace heating.

Other materials of better heat insulating value than the bare tin were tested. Numbers 3, 6, 10, 12, 15, 18, and 21, all show values which indicate that a large saving would be effected by their use. Some of them are expensive and not easy of application, but good selections may be made. The air-cell combinations Nos. 3 and 6 are excellent insulators, are easy to fit to basement leaders, are not expensive, and the latter, in particular, is not bulky.

The double wall tin pipes Nos. 10 and 12 are very efficient insulators and are easy to construct and to install. Other tests are in progress which are expected to establish still further the merits of this type.

The tests on galvanized iron specimens brought out the fact that the heat loss through this material is not greater than through bright tin of the same gage. This low heat radiating property is an argument in favor of the galvanized iron leader pipe. Nos. 18 and 21 are good insulations for the exterior of furnace casings, the heat loss through the latter being almost negligible. No. 21 is very easily applied.

The tests on drum No. 11 were made to determine the effect of transparent applications on the tin surface. Bakelite lacquer was used. The result was a slight increase in the heat loss. It was thought that the use of the lacquer would be justified in practice by its rust preventing qualities, but specimens exposed to steam laden air for long periods show no advantage for the protective coating.

Tests Nos. 20 and 23 were made for the purpose of ascertaining the effect of color upon the heat radiating value of a surface. Applications of white calcimine were made on a drum which was tested; then a coat of dull black calcimine was added and the drum re-tested; a final coating of white calcimine was applied and the drum again tested. The alternate tests with white calcimine checked very closely proving that the additional thickness of the calcimine was not sufficient to have any bearing on the results. Beyond demonstrating the superior radiating value of a dark surface, the tests have little significance.

Specimens Nos. 4 and 5 demonstrated the uneconomical effect due to increased heat loss of any kind of oil paint applications on heat pipes. A comparison of Nos. 1 and 4 will show the enormous increase in heat loss caused by painting bright tin heat pipes, and a comparison of Nos. 2 and 5 will show the similar wasteful effect of painting over the asbestos paper covering. However, the use of paint on asbestos paper has in its favor the moisture-proofing effect of the paint.

Other information of value may be found in the data given in the table. To use these data for the determination of the approximate heat loss from a heat pipe, it is only necessary to multiply the value of K for the surface by the surface area of the pipe exposed and further multiply by the difference in temperature between the air inside and outside the pipe, or,

$$\text{B. t. u. loss per hour} = K \text{ x Area in sq. ft. x } (t_1 - t_a)$$

On account of the difficulty of correctly measuring the temperature of the air near the inner surface of the pipe, the method of determining the loss from a pipe as here given, is only approximate.

VI. CORROBORATIVE TESTS

9. *The Auxiliary Air Plant.*—In order to show the connection between the work done on the steam drums already described and conditions obtaining in a warm-air system, the following account of experiments conducted on the Auxiliary Furnace Plant* which is shown in Fig. 6 of this bulletin is given. In these experiments, the weight of air flowing up the pipe was determined by the use of the steam-air meter which supplied the heat. Half way along the ten-foot length of the ten-inch leader pipe was located a traversing device (Fig. 8) which made it possible to get temperatures at any point across

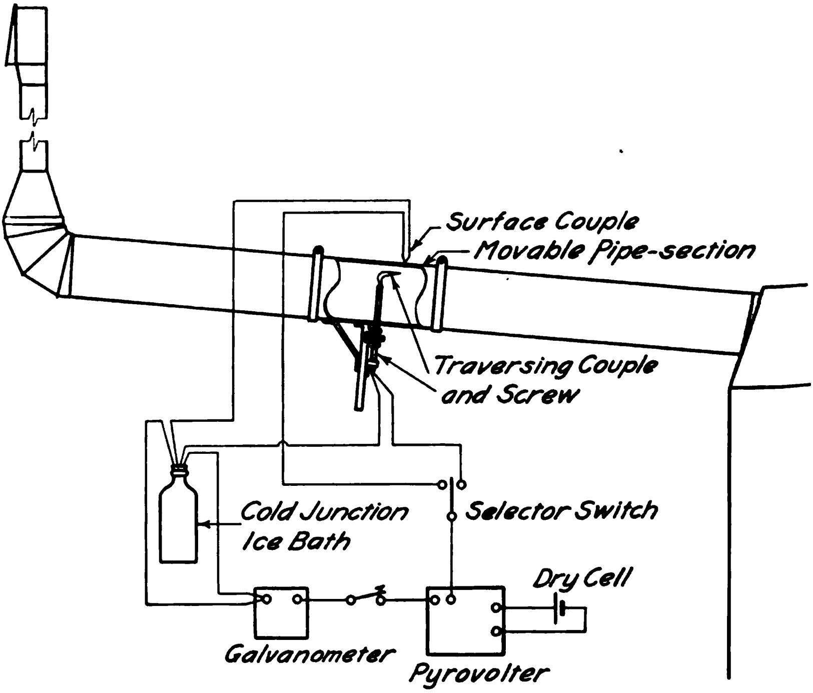


FIG. 8. DIAGRAM OF THERMOCOUPLE CONNECTIONS TO THE AUXILIARY TESTING PLANT

the pipe diameter by intervals of one-hundredth of an inch. A thermocouple was used in the traverse and its readings were accurate within one degree Fahrenheit. A second couple was tinned to the surface of the pipe and by rotation of the pipe (a short section could be turned) temperatures at any point on the surface in the plane of rotation of the couple could be determined.

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* University of Illinois Engineering Experiment Station Bulletin No. 112, "A Report of Progress in Warm-Air Furnace Research," by Prof. A. C. Willard.

10. *Temperature Measurement.*—The couples used in this work were made of copper and constantan wires of No. 22 gage. The junctions were silver soldered. Fig. 8 shows the wiring arrangement and the instruments used for two couples. As many couples may be used as there are contact points on the selector switch. Four were used on the leader pipe for the tests here described. The couples were calibrated individually in a hot oil bath over a range of 200 degrees, and calibration curves were carefully drawn. It is possible to repeat readings of the pyrovolter within 0.01 millivolt which by calibration is 0.4 degree Fahrenheit. This insures an accuracy of reading of one-half degree. As the couples were soldered to the surface of the pipe in some parts of the work, it was thought advisable to repeat the calibration after the couples were removed from the pipe. The constancy of the couples was found to be unaltered by the soldering to the pipe.

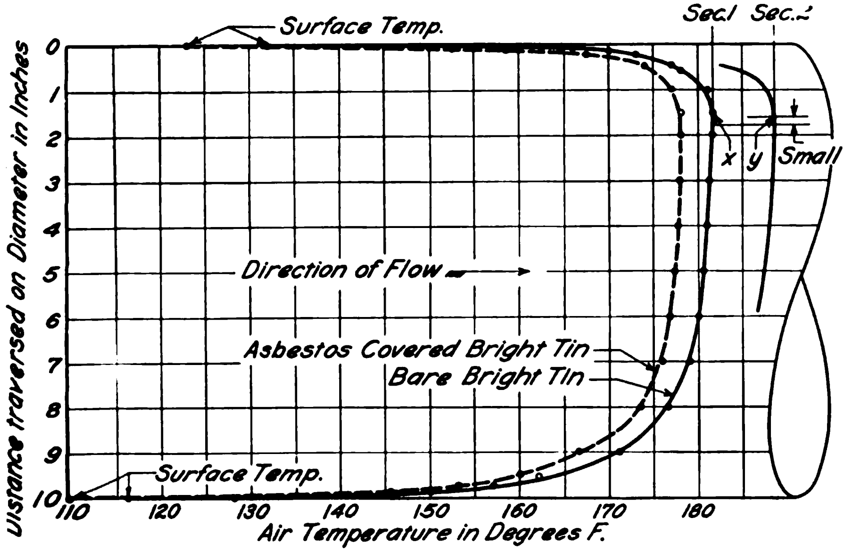


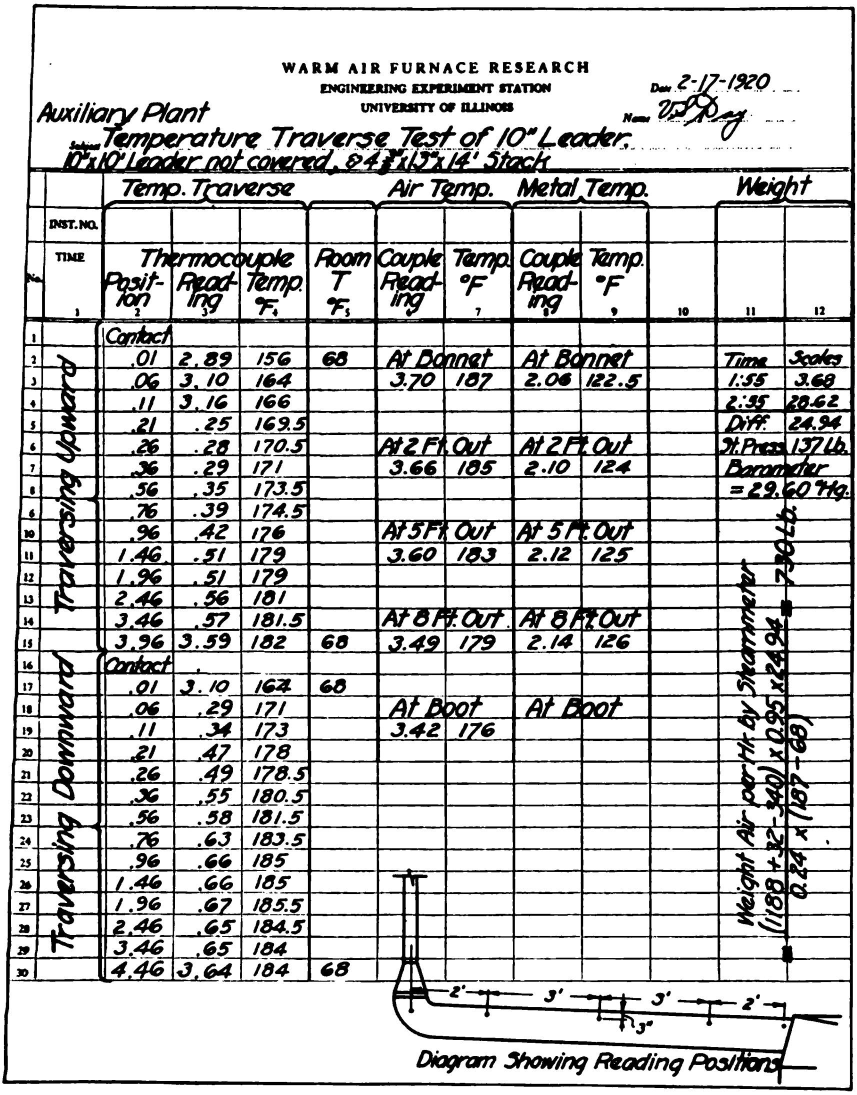
FIG. 9. TEMPERATURE TRAVERSE CURVES OF TEN-INCH LEADER PIPE

The use of thermometers for accurate temperature measurements in an air stream is not satisfactory. Thermometer readings will not be in agreement with thermocouple readings though both are suspended in close proximity in the same stream of moving air. For this reason thermocouples were used throughout these tests.

In Fig. 9 are given temperature traverse curves showing the variation in temperature across the ten-inch pipe. Curves are shown for both the asbestos paper-covered pipe and the bare pipe, all other conditions of the tests being identical. The curves demonstrate the heat-radiating value of the asbestos paper. Note that not only the air temperature but the surface metal temperature beneath the paper is lower in the case of the covered pipe, this fact indicating that the tin is conducting the heat to the asbestos covering which in turn radiates it more rapidly than does uncovered tin. Very exact means were taken to determine the temperature of the film of air in contact with the inner surface of the pipe. The traversing couple, made of wire 0.025 inch in diameter, was filed flat at the junction so that it was less than 0.02 inch thick. Measurements of the temperature were made with this thin couple at a distance from the pipe surface just great enough to cause a break in an electric circuit through the couple and the pipe, the break being indicated by a small voltmeter in the circuit. The distance was less than 0.01 inch from the pipe surface. The temperatures were found to differ from the metal temperature 15 to 30 degrees, the greater difference existing in the case of asbestos paper-covered pipe. (See the sample data sheet Fig. 10 for data on these measurements.)

The temperature change of the air flowing in the pipe was determined by the use of couples suspended in the air stream three inches below the top of the pipe. These couples correctly register the temperature drop of the mass of air between any two sections for the reason that the traverse curves are similar in shape at all sections along the pipe, and the error in reading the temperature due to a difference in the traverse curve is very slight. This fact is illustrated in Fig. 9 at Sec. 1 and Sec. 2. It will be seen that a great difference in the shape of the traverse curve would be necessary to cause serious error in determining the temperature drop along the path of flow of the air.

In measuring the temperature of the pipe surface, it was found that, whereas the air in the pipe dropped in temperature, the pipe itself showed a measurable increase in temperature away from the



WARM AIR FURNACE RESEARCH
ENGINEERING EXPERIMENT STATION
UNIVERSITY OF ILLINOIS

Date 2-17-1920
Name V.S. Day

Auxiliary Plant
Subject Temperature Traverse Test of 10" Leader.
10"x10' Leader not covered, 8-4 3/4"x13"x14' Stack

No.		Temp. Traverse				Air Temp.		Metal Temp.			Weight	
	INST. NO.											
	TIME 1	Thermocouple Position 2	Thermocouple Reading 3	Thermocouple Temp. °F 4	Room T °F 5	Couple Reading 6	Temp. °F 7	Couple Reading 8	Temp. °F 9	10	11	12
1		Contact										
2	Traversing Upward	.01	2.89	156	68	At Bonnet		At Bonnet			Time	Scales
3		.06	3.10	164		3.70	187	2.06	122.5		1:55	3.68
4		.11	3.16	166							2:35	28.62
5		.21	.25	169.5							Diff.	24.94
6		.26	.28	170.5		At 2 Ft. Out		At 2 Ft. Out			St. Press	137 Lb.
7		.36	.29	171		3.66	185	2.10	124		Barometer	
8		.56	.35	173.5							=29.60"Hg.	
9		.76	.39	174.5							Weight Air per Hr. by Shearmeter $\frac{(1188+32-340)\times 0.95\times 24.94}{0.24\times(187-68)} = 730$ Lb.	
10		.96	.42	176		At 5 Ft. Out		At 5 Ft. Out				
11		1.46	.51	179		3.60	183	2.12	125			
12		1.96	.51	179								
13		2.46	.56	181								
14		3.46	.57	181.5		At 8 Ft. Out.		At 8 Ft. Out				
15		3.96	3.59	182	68	3.49	179	2.14	126			
16	Traversing Downward	Contact										
17		.01	3.10	164	68							
18		.06	.29	171		At Boot		At Boot				
19		.11	.34	173		3.42	176					
20		.21	.47	178								
21		.26	.49	178.5								
22		.36	.55	180.5								
23		.56	.58	181.5								
24		.76	.63	183.5								
25		.96	.66	185								
26		1.46	.66	185								
27		1.96	.67	185.5								
28		2.46	.65	184.5								
29		3.46	.65	184								
30		4.46	3.64	184	68							

Diagram Showing Reading Positions

FIG. 10. DATA FOR A TEMPERATURE TRAVERSE TEST ON THE AUXILIARY FURNACE TESTING PLANT

furnace. This slight increase occurred when the pipe was covered as well as when bare. As this increase amounted to only about 3 degrees and was proportional to the length of pipe, it was considered permissible to use the temperature half way up the leader as the mean metal temperature.

11. *Calculation.*—The coefficient of emissivity for the pipe surface may be calculated since the heat loss through the surface of the pipe between any two sections is equal to the decrease in the heat content of the air in its passage through the length of pipe between the two sections, or,

$$0.24\ W\ (t_1-t_2) = A\ (t_s-t_a)\ K_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (3)$$

in which W is the weight of air flowing.

t_1-t_2 = the temperature drop of the air in the given length of pipe.
A = the area of the pipe exposed in the given length of pipe.
t_s-t_a = the drop in temperature between the metal of the pipe and the air.
K_2 = the coefficient of emissivity not corrected.

Solution of the equation will furnish a value for K_2, which will not, however, check or agree with the value determined in the steam drum tests of the same material. The variation may be easily explained since it is a well-established law that the coefficient of heat emissivity of a hot body varies with the temperature difference between the heating and the cooling medium. (See tests of radiators by J. R. Allen which demonstrate this fact).*

In the case of the heat pipe the temperature traverse showed a low air temperature near the inner surface of the pipe and also a correspondingly low temperature of the metal of the pipe. The result is a comparatively low value of t_s-t_a and according to the law, a low coefficient is to be expected.

The following case will illustrate: the pipe was covered with 12-pound asbestos paper. The surface couple showed that the tempera-

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* Paper by J. R. Allen, given before American Society of Heating and Ventilating Engineers, Jan. 28, 1920.

the paper was actually lower than the tempera-
re pipe.

17
=1.77 B. t. u. per sq. ft. per hr. per 1 degree F.

ne correction of 0.2 per cent per degree F. below
f 150 degrees which is used in making corrections
applies to this surface,* the value of K becomes:

K [150 − ($t_s - t_a$)]
02 (150 − 44)]
u. per sq. ft. per hr. per 1 degree F.

se agreement with the value of K = 2.08 as deter-
drum tests, and reported above.

n.—Enough tests have been made on this apparatus
rate the results obtained on the steam drums, and
e in progress in which more exacting methods are

[illegible]

LIST OF
PUBLICATIONS OF THE ENGINEERING EXPERIMENT STATION

Bulletin No. 1. Tests of Reinforced Concrete Beams, by Arthur N. Talbot. 1904. *None available.*

Circular No. 1. High-Speed Tool Steels, by L. P. Breckenridge. 1905. *None available.*

Bulletin No. 2. Tests of High-Speed Tool Steels on Cast Iron, by L. P. Breckenridge and Henry B. Dirks. 1905. *None available.*

Circular No. 2. Drainage of Earth Roads, by Ira O. Baker. 1906. *None available.*

Circular No. 3. Fuel Tests with Illinois Coal (Compiled from tests made by the Technological Branch of the U. S. G. S., at the St. Louis, Mo., Fuel Testing Plant, 1904-1907), by L. P. Breckenridge and Paul Diserens. 1908. *Thirty cents.*

Bulletin No. 3. The Engineering Experiment Station of the University of Illinois, by L. P. Breckenridge. 1906. *None available.*

Bulletin No. 4. Tests of Reinforced Concrete Beams, Series of 1905, by Arthur N. Talbot. 1906. *Forty-five cents.*

Bulletin No. 5. Resistance of Tubes to Collapse, by Albert P. Carman and M. L. Carr. 1906. *None available.*

Bulletin No. 6. Holding Power of Railroad Spikes, by Roy I. Webber. 1906. *None available.*

Bulletin No. 7. Fuel Tests with Illinois Coals, by L. P. Breckenridge, S. W. Parr, and Henry B. Dirks. 1906. *None available.*

Bulletin No. 8. Tests of Concrete: I, Shear; II, Bond, by Arthur N. Talbot. 1906. *None available.*

Bulletin No. 9. An Extension of the Dewey Decimal System of Classification Applied to the Engineering Industries, by L. P. Breckenridge and G. A. Goodenough. 1906. Revised Edition, 1912. *Fifty cents.*

Bulletin No. 10. Tests of Concrete and Reinforced Concrete Columns, Series of 1906, by Arthur N. Talbot. 1907. *None available.*

Bulletin No. 11. The Effect of Scale on the Transmission of Heat through Locomotive Boiler Tubes, by Edward C. Schmidt and John M. Snodgrass. 1907. *None available.*

Bulletin No. 12. Tests of Reinforced Concrete T-Beams, Series of 1906, by Arthur N. Talbot. 1907. *None available.*

Bulletin No. 13. An Extension of the Dewey Decimal System of Classification Applied to Architecture and Building, by N. Clifford Ricker. 1907. *None available.*

Bulletin No. 14. Tests of Reinforced Concrete Beams, Series of 1906, by Arthur N. Talbot. 1907. *None available.*

Bulletin No. 15. How to Burn Illinois Coal without Smoke, by L. P. Breckenridge. 1907. *None available.*

Bulletin No. 16. A Study of Roof Trusses, by N. Clifford Ricker. 1907. *None available.*

Bulletin No. 17. The Weathering of Coal, by S. W. Parr, N. D. Hamilton, and W. F. Wheeler. 1907. *None available.*

Bulletin No. 18. The Strength of Chain Links, by G. A. Goodenough and L. E. Moore. 1907. *Forty cents.*

Bulletin No. 19. Comparative Tests of Carbon, Metallized Carbon, and Tantalum Filament Lamps, by T. H. Amrine. 1907. *None available.*

Bulletin No. 20. Tests of Concrete and Reinforced Concrete Columns, Series of 1907, by Arthur N. Talbot. 1907. *None available.*

Bulletin No. 21. Tests of a Liquid Air Plant, by C. S. Hudson and C. M. Garland. 1908. *Fifteen cents.*

Bulletin No. 22. Tests of Cast-Iron and Reinforced Concrete Culvert Pipe, by Arthur N. Talbot. 1908. *None available.*

Bulletin No. 23. Voids, Settlement, and Weight of Crushed Stone, by Ira O. Baker. 1908. *Fifteen cents.*

**Bulletin No. 24.* The Modification of Illinois Coal by Low Temperature Distillation, by S. W. Parr and C. K. Francis. 1908. *Thirty cents.*

Bulletin No. 25. Lighting Country Homes by Private Electric Plants, by T. H. Amrine. 1908. *Twenty cents.*

Bulletin No. 26. High Steam-Pressure in Locomotive Service. A Review of a Report to the Carnegie Institution of Washington, by W. F. M. Goss. 1908. *Twenty-five cents.*

Bulletin No. 27. Tests of Brick Columns and Terra Cotta Block Columns, by Arthur N. Talbot and Duff A. Abrams. 1908. *Twenty-five cents.*

Bulletin No. 28. A Test of Three Large Reinforced Concrete Beams, by Arthur N. Talbot. 1908. *Fifteen cents.*

Bulletin No. 29. Tests of Reinforced Concrete Beams: Resistance to Web Stresses, Series of 1907 and 1908, by Arthur N. Talbot. 1909. *Forty-five cents.*

Bulletin No. 30. On the Rate of Formation of Carbon Monoxide in Gas Producers, by J. K. Clement, L. H. Adams, and C. N. Haskins. 1909. *Twenty-five cents.*

Bulletin No. 31. Tests with House-Heating Boilers, by J. M. Snodgrass. 1909. *Fifty-five cents.*

Bulletin No. 32. The Occluded Gases in Coal, by S. W. Parr and Perry Barker. 1909. *Fifteen cents.*

Bulletin No. 33. Tests of Tungsten Lamps, by T. H. Amrine and A. Guell. 1909. *Twenty cents.*

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DISSOLVED GASES IN GLASS

BY
EDWARD W. WASHBURN
FRANK F. FOOTITT
ELMER N. BUNTING

BULLETIN No. 118

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BULLETIN No. 118 DECEMBER, 1920

DISSOLVED GASES IN GLASS

BY

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ENGINEERING EXPERIMENT STATION
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DISSOLVED GASES IN GLASS

I. Introduction

1. *Foreword.*—The work described in the following pages was begun in June, 1917, as part of a program of research on some of the problems connected with the manufacture of optical glass. The first experiments were carried out by Mr. **Frank F. Footitt**, at that time Research Assistant in the Engineering Experiment Station. Mr. Footitt later joined the Signal Corps of the United States Army and was detailed at the University to assist in the continuation of the research. His part in the work continued until he was honorably discharged from the service in February, 1919. The results given in the first three chapters of the present paper are based upon Sgt. Footitt's experiments, an account of which was given before the Pittsburgh meeting of the American Ceramic Society in February, 1919. After Sgt. Footitt's discharge the investigation was dropped until January, 1920, when it was again taken up with the assistance of **Dr. Elmer N. Bunting**, who is continuing it at the present time.

2. *Purpose of the Investigation.*—All varieties of glass, even at ordinary temperatures, are in the liquid state of aggregation. They are liquids which have been cooled through their normal crystallization interval so rapidly that there has not been time for crystallization ("devitrification") to occur. Instead, the viscosity of the liquid has been increased to such a large value that the molecules do not have sufficient freedom of motion to permit the rearrangements necessary for the formation and growth of crystals. The liquid has thus been supercooled until it has become a solid. In principle any liquid can by supercooling be brought into the condition of a glass, but since it still remains a liquid, it should possess the characteristic properties of liquids, including the power to hold gases in a state of solution.

During the process of manufacturing glass, large quantities of gas, mainly carbon dioxide, oxygen, and nitrogen, are evolved from the batch owing to the occurrence of chemical reactions such as the following:

$$Na_2CO_3 + SiO_2 = Na_2SiO_3 + CO_2$$
$$4\,KNO_3 + 2\,SiO_2 = 2\,K_2SiO_3 + 2\,N_2 + 5O_2$$
$$2\,PbO_2 + 2\,SiO_2 = 2\,PbSiO_3 + O_2$$

If ammonium nitrate, NH_4NO_3, is employed in "blocking"* the glass, water vapor will also be evolved during the fining. The glass will thus be saturated with these gases at the partial pressures which prevail at the end of the "fining" operation.

On cooling the glass, these gases should remain in solution, and glass in the finished state may therefore be expected to contain appreciable quantities of these dissolved gases. Since no actual data concerning the nature or amounts of such dissolved gases were available, the experiments described below were undertaken for the purpose of throwing some light on this question. These experiments are to be regarded as preliminary to a more extended investigation of these dissolved gases, and of their influence upon the properties of the finished glass, and its behavior during use.

In addition to the account of the experiments conducted to date, and their results, there will be found in the following pages some discussion of the relation between adsorbed and dissolved gas, the influence of dissolved gases upon the properties and behavior of glass, and the use of the vacuum furnace in the manufacture of glass.

3. *Acknowledgments.*—For samples of glass used in the present investigation we are indebted to the United States Bureau of Standards, and to the Pittsburgh Plate Glass Company. The Signal Corps, and later the Aircraft Production Board, made possible the prosecution of the work during the war by the detail of Sgt. Footitt as Research Assistant.

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* The term "fining" or "plaining" is applied to the operation of eliminating bubbles from the molten glass. This may be accomplished by heating the glass to a sufficiently high temperature to cause the bubbles to expand and rise to the top of the melt. If this method is not effective the operation of "blocking" is employed. This consists in inserting into the melt, with the aid of an iron rod, a potato, a piece of green wood, a pellet of ammonium nitrate, or in general any material which will give a copious evolution of gas in the form of large bubbles which will rise through the melt and gather up the small bubbles in their path.

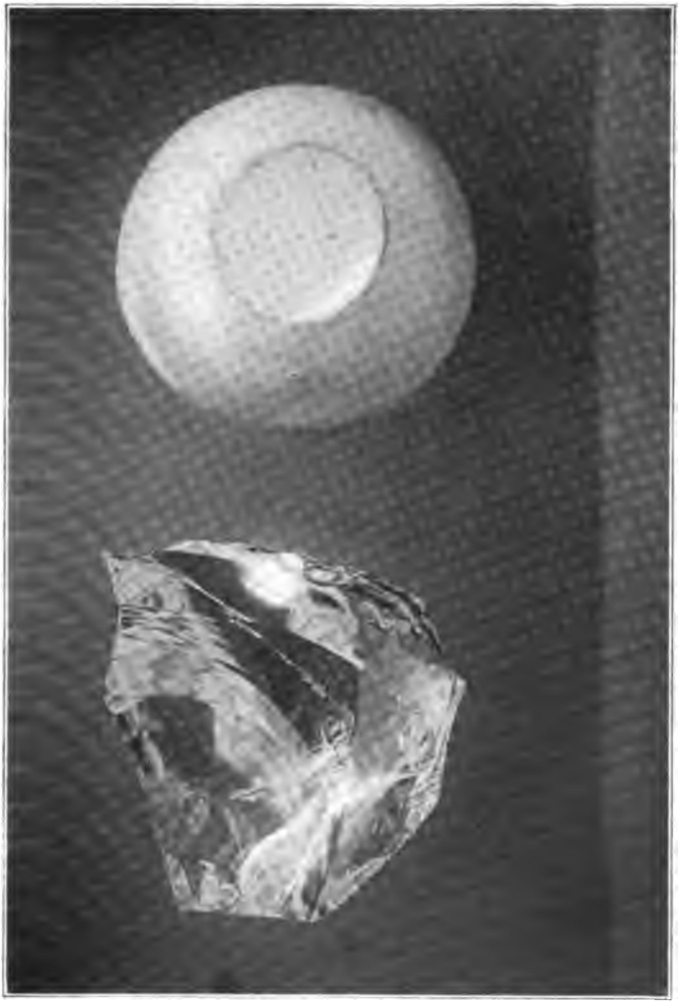

Fig. 1. Melting Pot, with Block of Glass before Melting

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II. DEMONSTRATION OF THE EXISTENCE OF DISSOLVED GASES IN FINISHED GLASS

4. *The Method Employed.*—In order to demonstrate the existence of dissolved gases in considerable quantity in a piece of perfectly clear homogeneous glass, the method of "sudden evacuation" may be employed. In this method the piece of glass to be investigated is melted under atmospheric pressure in a vacuum furnace which can be connected through a valve to a large evacuated tank. When the temperature of the glass has reached about 1200 deg. C. the valve is opened quickly, thus causing a sudden drop of pressure within the furnace.

This experiment is similar to the opening of a siphon of soda water, and if the glass contains dissolved gases a similar result would be expected, that is, there should be a sudden evolution of gas from the glass, causing it to expand in volume and to effervesce vigorously.

5. *The Glass.*—The glass employed in the first experiment was a piece of barium flint optical (1.6053-43.6) having the following composition, as determined by the Bureau of Standards:

Oxide . . .	SiO_2	As_2O_5	PbO	ZnO	BaO	K_2O
Mole (per cent)	64.5	0.15	9.73	9.22	10.2	6.24

A piece free from bubbles was selected, placed on a table beside an inverted melting pot, and photographed. (See Fig. 1.)

6. *The Furnace.*—The vacuum furnace and the details of the heating element and thermocouple installation are shown in Figs. 2 and 3, which are self explanatory. The outlet tube was connected to a Nelson rotary vacuum pump and also, through a valve, to a large vacuum tank (A, in Fig. 4) having a capacity about 100 times that of the furnace chamber.

7. *Experimental Procedure.*—The melting pot containing the piece of glass was placed inside the heating chamber (Fig. 2) and this in turn placed within an insulating cylinder supported on the

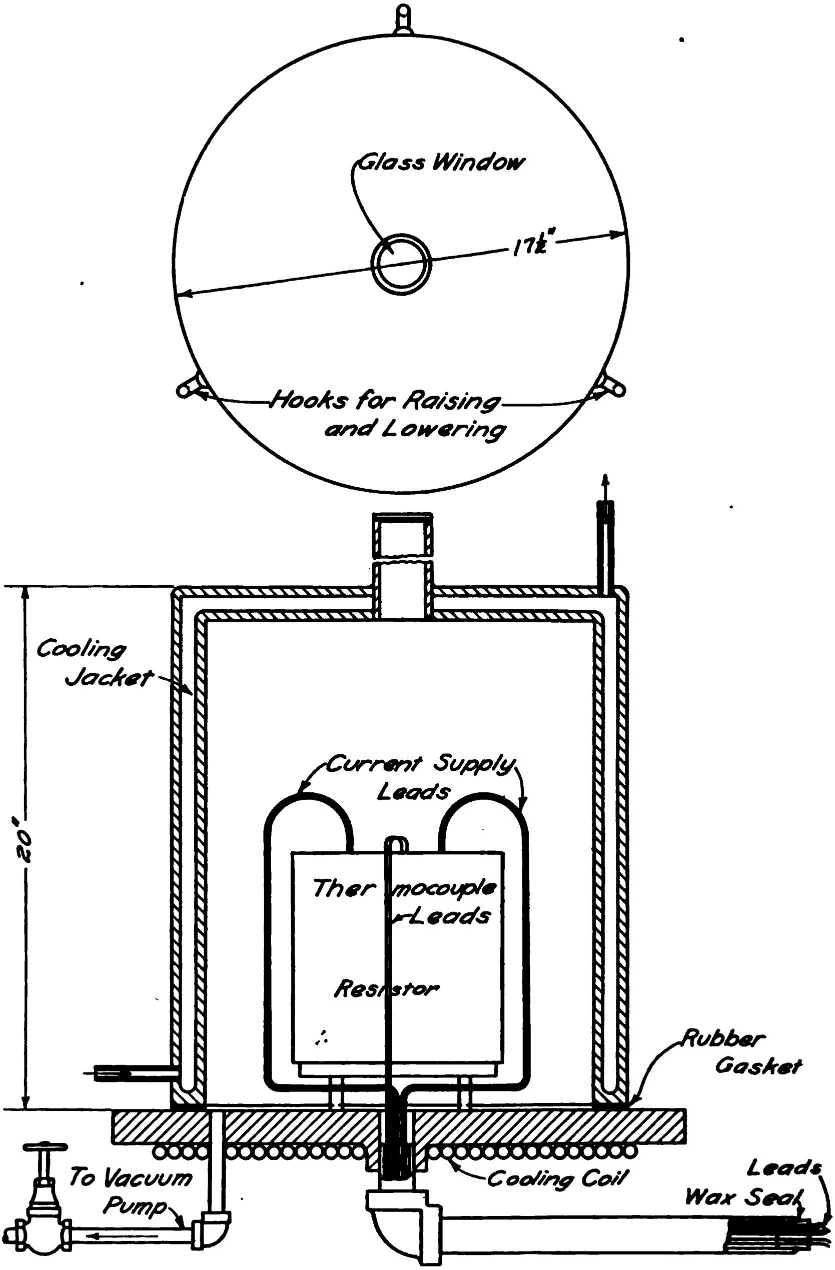

FIG. 2. DETAIL OF VACUUM FURNACE

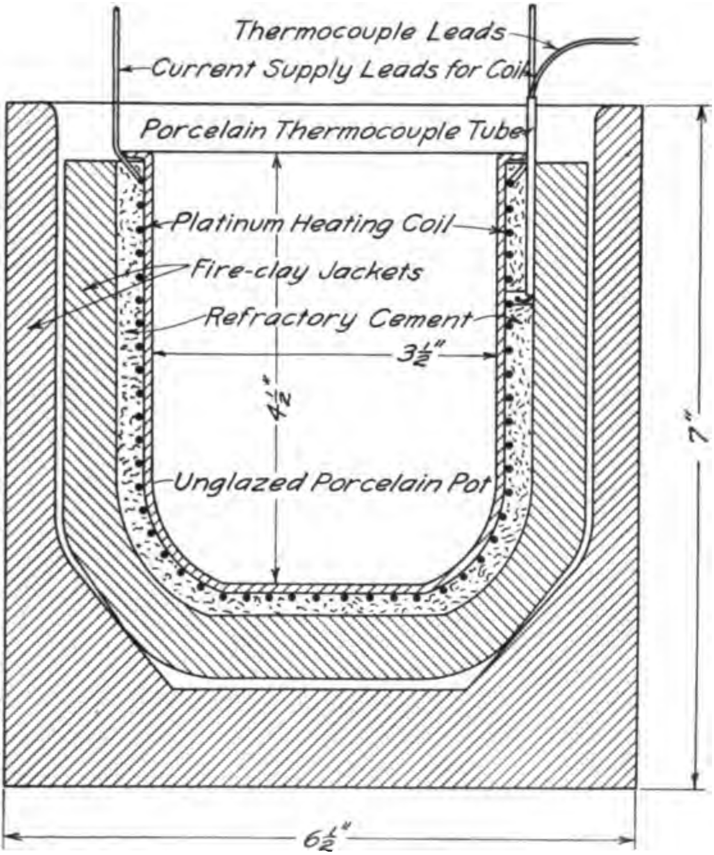

FIG. 3. DETAIL OF POT, RESISTOR, AND INSULATION

furnace base as shown (Fig. 3). The water cooled iron dome (see Fig. 4) was then lowered into place on its rubber gasket and the current started in the heating coil. When the glass had attained a temperature of about 1200 deg. C. the valve connecting the outlet with the large vacuum tank was quickly opened.

This tank had been previously evacuated to a pressure of 1 inch of mercury, and as soon as pressure equalization had taken place, as indicated by the manometer, the valve was quickly closed, the Nelson pump started, and the pressure in the furnace chamber brought down rapidly to less than 1 cm. of mercury. The heating current was then cut off and the furnace allowed to cool with the vacuum on.

8. *The Result.*—On opening the furnace most of the glass was found outside of the pot, standing above it in the form of a large white mass of foam. This was broken away from the pot and photographed as before, beside the inverted pot. The result is shown in Fig. 5. By comparing Figs. 1 and 5 an idea of the increase in volume associated with the evolution of the dissolved gases may be obtained. This amounted to about six times the volume of the original piece. The existence of considerable quantities of gas in a state of solution in the glass was thus demonstrated.

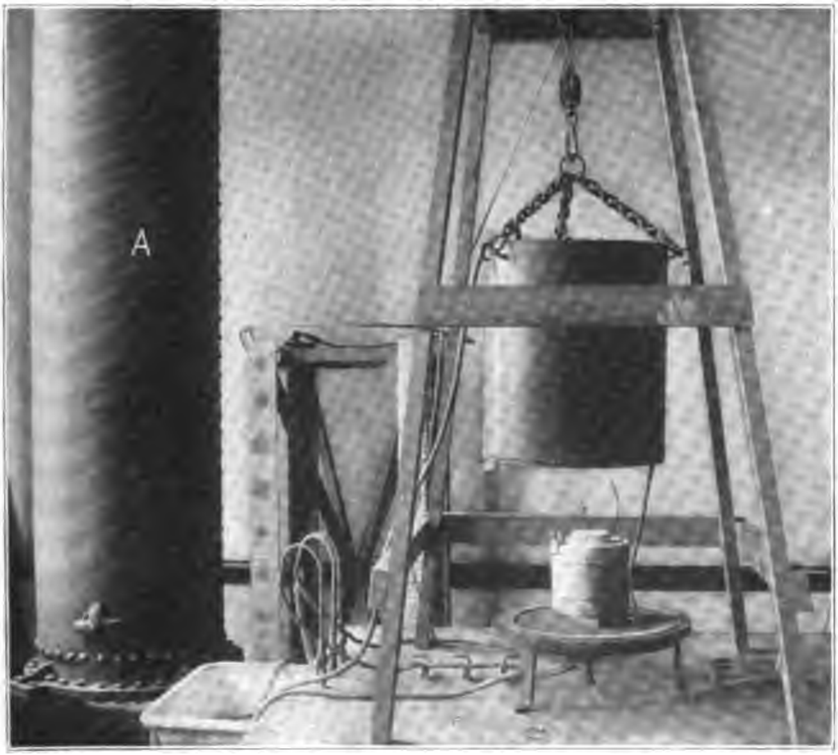

FIG. 4. VACUUM FURNACE AND LARGE VACUUM TANK

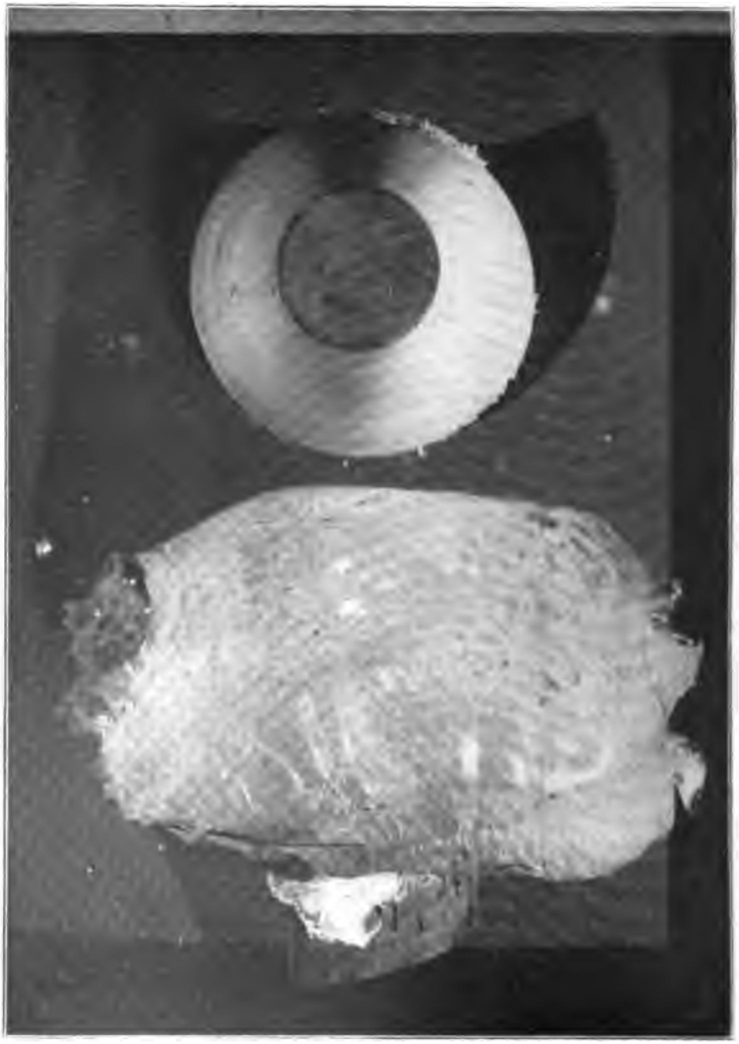

FIG. 5. MELTING POT, WITH BLOCK OF GLASS AFTER MELTING AND EVACUATING

III. PARTIAL ANALYSIS OF THE GASES EVOLVED FROM THE GLASS

9. *The Apparatus and Method.*—The furnace employed was that used in the preceding experiment. The large vacuum tank was disconnected, however, and the outlet tube V was connected to a Gaede high vacuum pump, through an analysing train. The method consisted briefly in evacuating the furnace until all adsorbed gases were removed, melting the glass, drawing the evolved gases out through the analysing train, and finally washing out the furnace with pure nitrogen. All connections throughout the system were sealed glass joints, or glass-to-glass joints covered with heavy rubber tubing and coated with a beeswax-rosin mixture.

10. *The Analysing Train.*—The analysing train consisted of the following elements in the order named, starting from the furnace end:

(1) a series of six gas wash bottles containing standard barium hydroxide solution, and having their delivery tubes drawn down to capillary openings so as to produce a stream of small bubbles through the solution when in operation:

(2) a drying tower containing pumice and sulphuric acid:

(3) a glazed porcelain combustion tube containing copper gauze and provided with a heating coil. Two pieces of copper gauze previously reduced in hydrogen and then weighed were placed in series in the combustion tube, which was kept at 700 deg. C. during the run.

Before the experiment was begun the analysing train was thoroughly washed out with pure nitrogen in order to remove all air. The nitrogen used for this purpose was purified by passing it over hot copper, and through wash bottles containing barium hydroxide solution. The nitrogen thus purified gave zero test for both carbon dioxide and oxygen.

11. *Flushing the Furnace.*—In order to remove adsorbed gases from the glass pot and the insulating materials, the following procedure was adopted. The furnace was assembled as shown in Fig. 3 with the melting pot in place. The Gaede pump was started and the pressure in the furnace reduced to 0.02 mm. At the same time the current was started in the heating coil and the pot heated to a temperature several hundred degrees higher than that employed in the melting operation. The furnace was kept hot and the Gaede

pump in operation for several hours. Pure nitrogen was then admitted to the furnace chamber until atmospheric pressure was attained, after which the nitrogen was pumped out. This washing with nitrogen was repeated several times and the furnace finally allowed to cool while filled with nitrogen.

12. *Melting the Glass.*—When the nitrogen filled furnace was entirely cold, the water cooled dome was hoisted sufficiently to permit a weighed quantity (about 350 grams) of glass to be dropped into the melting pot, after which the dome was immediately lowered into place and the Gaede pump started. At the same time the resistor was heated to just below red heat, and after the pressure had fallen to 0.02 mm. the furnace was again flushed two times with pure nitrogen.

Finally, with a vacuum of 0.01 to 0.02 mm. in the furnace, it was sealed by closing a stop-cock, and the temperature of the pot was raised to about 1000 deg. C. and kept there for one hour. The pressure was then noted and the temperature of the pot allowed to drop to about 650 deg. C. after which pure nitrogen was admitted until atmospheric pressure had been reached.

With the resistor maintained at about 650 deg. C. the contents of the furnace were then pumped out through the analysing train and the furnace washed out with nitrogen, the washings being also pumped out through the analysing train. The furnace was finally allowed to stand full of pure nitrogen until time for the next experiment.

13. *The Results.*—The results obtained in four separate experiments, using pieces of the same block of glass, are shown in Table 1. It will be noticed that oxygen and carbon dioxide are present in solution in the glass to the extent of 0.1 per cent of its weight. Part, perhaps the greater part, of the carbon dioxide is present in the combined state as carbonate, and some of it would therefore be retained in the glass even under a vacuum of 0.02 mm.

TABLE 1

PER CENT BY WEIGHT OF OXYGEN AND OF CARBON DIOXIDE DISSOLVED IN A BARIUM-FLINT OPTICAL GLASS

GAS	WEIGHT PER CENT					MOLES PER LITER
	1	2	3	4	Mean	
O_2.............	0.078	0.092	0.074	0.086	0.08	0.07
CO_2.............	.017	.023	.031	....	.02	0.01

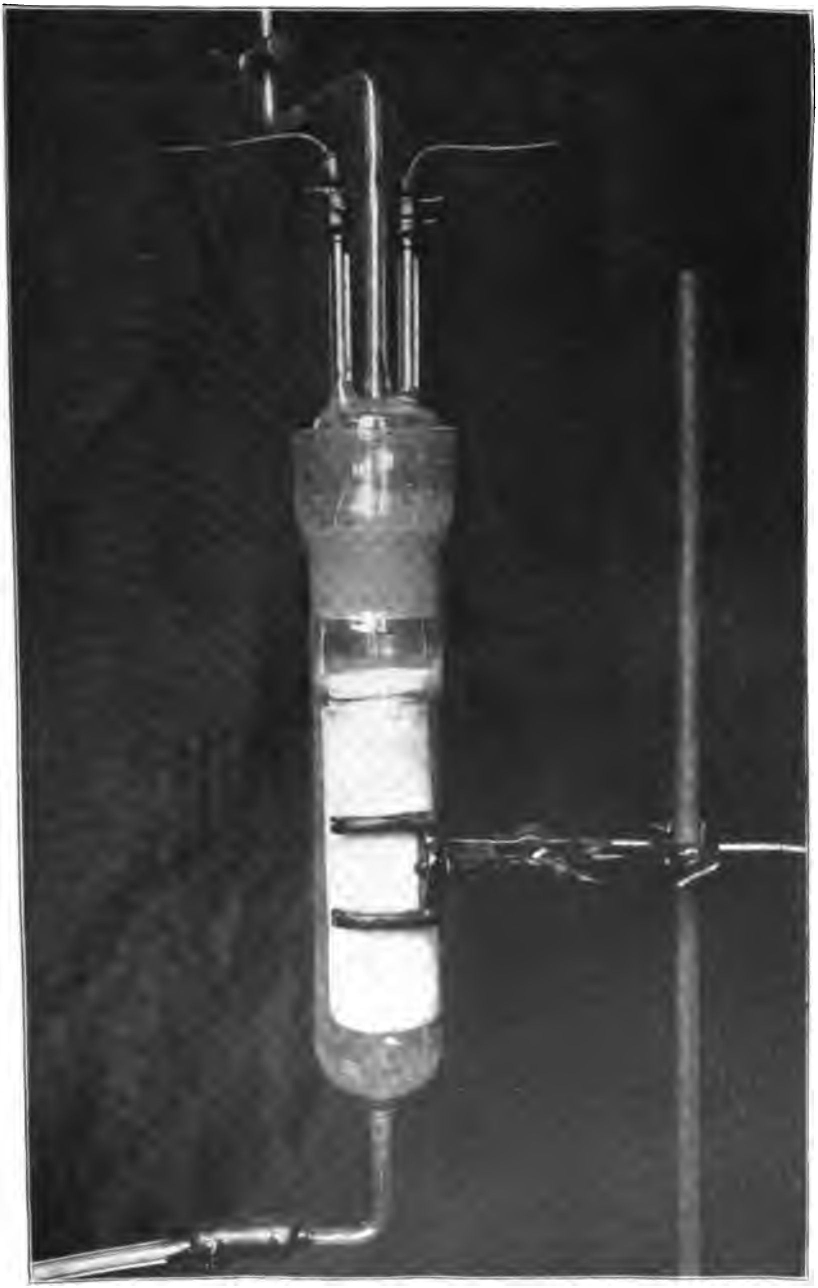

FIG. 6. APPARATUS FOR MEASURING AND ANALYSING THE DISSOLVED GASES IN GLASS

IV. A SPECIAL APPARATUS FOR BOTH MEASURING AND ANALYSING THE DISSOLVED GASES IN GLASS

14. *Description of the Apparatus.*—The experiments described in the preceding section gave satisfactory evidence of the existence of dissolved oxygen and carbon dioxide in considerable amounts in finished glass. The apparatus and the method employed in these experiments were, however, rather cumbersome and complicated, and it was very difficult to make sure that no leakage of atmospheric gases into the evacuated furnace took place. The method, moreover, did not yield a measure of the total amount of the dissolved gases.

In order to eliminate these drawbacks a new vacuum furnace was designed, constructed entirely of glass and porcelain, which could readily be made perfectly gas tight, and which also permitted all of the gas evolved by the glass to be both measured and analysed. The final form of this apparatus is shown in Figs. 6 and 7.

The vacuum casing of the furnace consisted of a pyrex glass tube 5 cm. in diameter and 13 cm. high, provided with a ground glass stopper having a mercury seal at the joint. The melting pot was a cylindrical porcelain tube, 3 cm. in diameter and 13 cm. high. It was wound with platinum wire and slipped into a tightly fitting porcelain protecting tube. An outer more loosely fitting protecting tube completed this portion of the apparatus, which was suspended inside of the glass tube by means of two heavy copper leads which passed out through the capillary tubes, T_1 and T_2. The joint between these lead wires and the top of the capillary tubes was made tight by a rubber plug covered with a beeswax-rosin mixture.

15. *Determination of Free Volume of Furnace.*—For this purpose a calibrated 230 cu. cm. flask containing air at atmospheric pressure was attached at M and the stop-cock S_1 was closed. The furnace, containing the melting pot and its protecting tubes, was then evacuated to a pressure of 0.1 mm. of mercury and, after the connection to the pump had been closed, stop-cock S_1 was opened and the manometer reading again taken. The volume of the flask being known, and the change in pressure which occurred on connecting it to the evacuated apparatus, the free volume of the latter was calculated to be 475 cu. cm.

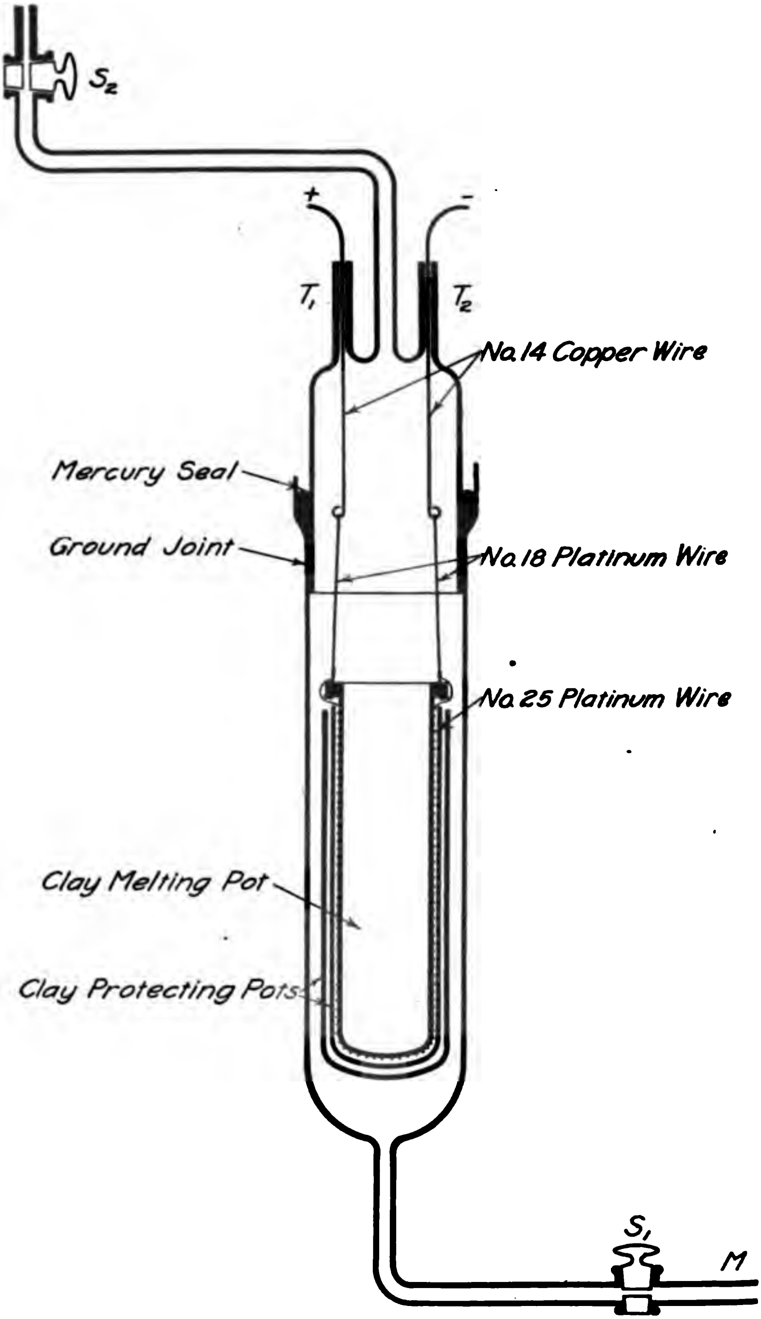

FIG. 7. DETAIL OF APPARATUS FOR MEASURING AND ANALYSING THE DISSOLVED GASES IN GLASS

16. *Experimental Procedure.*—The following procedure was employed in measuring and analysing the dissolved gases in glass. A weighed sample of glass—in some cases, 25 grams, in others, 50 grams,—was placed in the melting pot and the whole apparatus assembled as shown in the figure. With stop-cock S_1 closed, the apparatus was evacuated to a pressure of 0.1 mm. of mercury, and at the same time a sufficient current was passed through the heating wire to heat the pot and protecting tubes to about 400 deg. C., at which temperature no dissolved gas is given up by the glass. This preliminary heating and evacuating was necessary in order to remove adsorbed moisture from the porcelain. The connection to the pump was then closed and the whole apparatus allowed to stand for several hours in order to make sure that it was perfectly tight, this fact, of course, being indicated by an absolutely constant manometer reading.

Sufficient current was then passed through the heating coil to raise the temperature of the glass to 1400 deg. C. and the heating was continued till no more gas was evolved from the molten glass, as shown by a steady manometer reading. During this heating a blast of air was directed on the ground glass joint. The apparatus was then cooled to room temperature and the manometer reading was recorded. The free volume of the furnace being known, the total amount of gas evolved by the glass could be calculated. The total time required for a run was from two to three hours.

After the final manometer reading had been taken, the stop-cock leading to the manometer was closed, the manometer disconnected, and a small Orsat apparatus connected in its place. The tube M was then connected to an adjustable mercury reservoir, the mercury filling the tube completely up to the stop-cock. This stop-cock was opened and the furnace completely filled with mercury, all of the gas being driven out ahead of the mercury into the Orsat apparatus, where it was analysed for carbon dioxide and oxygen, any residual gas being considered nitrogen. The accuracy of the chemical analysis was about one per cent.

V. THE GAS CONTENT OF THREE TYPES OF COMMERCIAL GLASS

17. *A Barium Flint Optical Glass.*—This was the same type of glass as that used in the experiments described in Chapter III, but was obtained from the Pittsburgh Plate Glass Company, and may have differed somewhat in composition. Its index of refraction was given by Dr. Hostetter as "about 1.605, and its ν value, about 43.6."

Two experiments on 50 gram portions, and one on a 25 gram portion, of one block of glass gave total volumes of dissolved gases (measured under standard conditions) of 15.6, 14.3 and 8.04 cu. cm. respectively. The average is 15.3 cu. cm. for 50 grams of glass, amounting to 1.1 times the volume of the glass itself. Two samples of another block of the glass gave a volume of gas (under standard conditions) equal to half the volume of the glass. The history of the two blocks used in these experiments is not known. They were taken from a 25 lb. lot of cullet, and may have come from two entirely different melts. It is, of course, to be expected that the gas content of finished glass will depend very materially upon the melting and fining procedure which has been followed.

The gas from the second block of glass was analysed, and was found to consist of 25 per cent carbon dioxide and 75 per cent oxygen. If any nitrogen was present it was less than one per cent.

18. *A Light Flint Bulb Glass.*—The sample of glass used had the following composition according to the manufacturer's analysis:

Oxide . . .	SiO_2	PbO	Al_2O_3	CaO	Na_2O
Mole (per cent)	75.0	7.15	0.45	0.60	16.76

Two melts of 50 grams each were made and they gave respectively 3.2 and 3.5 cu. cm. of gas under standard conditions. The dissolved gas thus amounted to 0.2 times the volume of the glass itself. Analysis of the gas gave 58 per cent carbon dioxide, 24 per cent oxygen, and 18 per cent nitrogen. The density of the glass was 2.89.

19. *A Borosilicate Laboratory Glass.*—The glass investigated had approximately the following composition:

Oxide . . .	SiO_2	B_2O_3	As_2O_5	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O
Mole (per cent)	83.0	10.5	0.2	1.2	0.1	0.3	0.1	4.4	0.1

Twenty-five grams of glass gave, on melting, a volume of gas (under standard conditions) equal to 0.2 times the volume of the glass. On analysis the gas was found to consist of 26 per cent carbon dioxide, 37 per cent oxygen, and 37 per cent nitrogen.

TABLE 2

SUMMARY OF RESULTS ON THE AMOUNTS OF DISSOLVED GASES IN FINISHED GLASS

	VOLUME PER CENT S.T.P.				WEIGHT PER CENT				CONCENTRATION MOLES PER LITER		
GLASS	O_2	CO_2	N_2	Total	O_2	CO_2	N_2	Total	O_2	CO_2	N_2
Barium flint .1.....	83	27	<1	110	0.035	0.011	....	0.046	0.033	0.011	....
Barium flint .2.....	36	12	<1	48	.015	.0045	....	.020	.016	.005	....
Light flint.........	4.5	10	3	18	.0045	.014	0.0025	.021	.004	.010	0.003
Borosilicate........	6	5	6	17	.0036	.0035	.0031	.010	.0028	.002	.0028
Water at 0 deg. C.									.0023	.080	.0010

20. *Discussion of the Results.*—The results obtained with the above three varieties of glass are summarized in Table 2. Owing to lack of data concerning the melting schedule and finishing operation used in the melts from which the samples studied originated, it is impossible to correlate the results obtained with the manufacturing procedure.

The quantity and nature of the gases present in the finished glass must obviously depend upon the batch composition and the melting and finishing procedures. The influence of the latter factor is probably responsible for the different results obtained with the different samples of the barium flint optical.

It is not probable that any appreciable quantities of gas are absorbed by the glass from the atmosphere of the furnace, except possibly in the case of glasses which are mechanically stirred for a long period. This conclusion seems to be borne out by the absence of nitrogen from the barium flint glass. The dissolved gas must therefore originate from the gases given off by the batch itself during the melting and fining processes.

At the end of the melting period, just before the fining operation begins, the glass usually contains numbers of small bubbles in which, owing to the high surface tension of molten glass, the gas is under a pressure greater than atmospheric. At the end of the fining operation the glass is therefore probably still somewhat supersaturated with gas, since, owing to its high viscosity, it cannot very rapidly give up this extra dissolved gas. The higher the finishing temperature, and the longer the glass is held at high temperatures, the smaller should be the amount of dissolved gas remaining in the finished glass. This conclusion seems to be borne out by the results obtained with the borosilicate glass, which is a glass requiring very high finishing and working temperatures. The great preponderance of acidic constituents in this glass may, however, be partially responsible for the small quantity of carbon dioxide found, since as shown by Niggli,* a good part of the dissolved carbon dioxide in glass is probably combined with the basic constituents.

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* Niggli, Paul, "The Phenomena of Equilibria between Silica and the Alkali Carbonates." Jour. Amer. Chem. Soc., Vol. 35, 1706 (1913).

VI. THE SIGNIFICANCE OF DISSOLVED GASES IN GLASS

21. *The Relation between Adsorbed and Dissolved Gas.*—It has long been recognized that glass in common with many other substances displays a strong tendency to adsorb, that is, to condense upon its surface, gases with which it is in contact.*

Adsorption may indeed be regarded as a type of solution in which the dissolved molecules do not penetrate below the surface layer of the adsorbent. Such a "surface solution" will therefore ordinarily be saturated when the surface of the adsorbent is covered with a layer of the adsorbed material one molecule deep and with its molecules close-packed laterally.†

Adsorption may sometimes be accompanied by a gradual penetration of the adsorbed material beneath the surface layer of the adsorbent, that is, it may be accompanied by ordinary or "volume" solution; but in the case of glass at low temperatures, such solution will probably be confined to the superficial layers. Adsorbed or superficially dissolved gases are thus to be distinguished from the dissolved gases studied in the present investigation, which are more or less uniformly disseminated throughout the whole mass of the glass. Langmuir‡ has found that water vapor is adsorbed and then slowly dissolved by glass. He also found that lamp bulbs when heated in vacuo evolved adsorbed carbon dioxide and nitrogen in addition to water vapor.

Recently Sherwood§ has devised a dynamic method for studying the gases evolved by glass when heated in vacuo to temperatures below its softening point. He found that adsorbed gases could be removed completely by heating to 200 deg. C. in vacuo and that the amount of such gases corresponded to a layer about one molecule deep over the surface of the glass. On subsequent heating to 500 deg. C. a further evolution of gas occurred, which he attributed to "chemical reactions" occurring within the glass.

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* Cf. Guichard, M., "Sur les gaz dégagé des parois des tubes de verre." Bull. Soc. Chim. 100, 440 (1911).

† For a more detailed discussion of the relation between adsorption and solution see Washburn, E. W., "Introduction to the Principles of Physical Chemistry," Ed. 2, Chap. XXV, The McGraw-Hill Book Company, New York, 1921.

‡ Langmuir, I., "The Adsorption of Gases on Plane Surfaces of Glass, Mica and Platinum," Jour. Amer. Chem. Soc., Vol. 38, 2283-4 (1916); Ibid., Vol. 40, 1387 (1918).

§ Sherwood, R. G., "Gases and Vapors from Glass," Phys. Rev., Vol. 12, 448 (1918).

The well known jump in pressure within an exhausted glass vessel which occurs when it is "sealed off" and the subsequent deterioration of the vacuum with time has been studied by Shrader.* He concludes that: "The vacuum in sealed vessels deteriorates with time, rapidly at first, and then more slowly, and subsequent heating, even at temperatures lower than the heat-treating temperature, results in increase of pressure due to further liberation of the gases and vapors from the glass. No connection between different samples of the same glass or different glasses can be established. It is quite probable that there are variations in the properties of different samples of the same glass quite as great as the variations between different glasses of about the same grade."

There is every reason to believe that the dissolved gases in glass play an important role in the behavior described by Shrader. Certainly the jump in pressure which occurs during the sealing-off process can be ascribed to this source, and it seems entirely probable that gas-free glass would be superior in many respects to ordinary glass for the manufacture of high vacuum apparatus.

The adsorption of various gases by glass and their subsequent evolution with vacuum-heat treatment have been studied, particularly with respect to the production and maintenance of high vacua, by Ulrey† in a recent investigation which at the time of writing is available only in abstract. His conclusions in the main substantiate those already referred to, but the following may be mentioned:

> (1) "Glass from which practically all absorbed gases have been removed by melting in vacuo subsequently reabsorbed gases from the atmosphere at room temperature."
>
> (2) "At temperatures up to the softening point, diffusion of gases of the atmosphere through glass does not take place."

With reference to his first conclusion, a distinction should be drawn between absorbed or dissolved gases and adsorbed gases. The removal of the former by melting in vacuo does not, of course, affect the ability of the glass to adsorb gases from the atmosphere, the latter being an entirely independent process.

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* Shrader, J. E., "Residual Gases and Vapors in Glass Bulbs," Phys. Rev., Vol. 13, 437 (1919).

† Ulrey, D., "Evolution and Absorption of Gases by Glass," Abstract in Phys. Rev., Vol. 14, 160 (1919).

The evidence for his second conclusion not being available, its exact significance is not entirely clear. The fact that the atmospheric gases seem able to diffuse through quartz glass at comparatively low temperatures renders it not improbable* that a similar behavior might be exhibited by some of the ordinary commercial glasses under some circumstances, although doubtless to a considerably less extent.

22. *The Influence of Dissolved Gases upon the Properties and Behavior of Glass.*—Evolution of dissolved gas in the form of bubbles tends to occur whenever the pressure on glass, while in a fluid condition, is decreased. Such a decrease in pressure will occur during the manufacturing operation whenever there is a marked fall in the barometer, and it would be interesting to know whether there is any record of troubles with "seedy" glass accompanying periods of barometric depression.

A condition of reduced pressure with a consequent evolution of bubbles of gas also results from the strains set up by the contraction of the glass itself. If the outside of a mass of glass be allowed to solidify while the interior is still in a fluid condition, it is evident that the gradual solidification of the remaining glass must bring about a tension upon the still fluid portions; and this decrease in pressure will cause them to evolve their dissolved gases, with the consequent formation of a mass of bubbles in those portions of the glass which remain longest in the fluid condition. Some interesting examples of the formation of seed from this cause have been described by Williams.†

Still another instance of the occurrence of reduced pressure during manufacturing operations is met with in cases where the glass is "gathered" by suction, as in the case of the Owens machine. If the glass when it reaches the gathering machine is supersaturated with dissolved gases, the operation of gathering will evidently result in the formation of seed, some of which will not disappear again when the suction is released. If the glass at the moment of gathering is undersaturated with the dissolved gases, as will be the case if it has been kept long enough at a sufficiently high temperature before reaching the gathering machine, the suction may still result in the momentary appearance of seeds, but these will be largely of the vacuum type and not permanent; if permanent, they will probably be exceedingly small, after the glass is finished.

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* Cf. Le Chatelier, "La Silice et les Silicates," p. 94, Hermann et Fils, Paris 1914; Mayer, E. C., "Leakage of Gases through Quartz Tubes," Phys. Rev., Vol. 4, 283 (1915).

† Williams, A. E., "Observations on the Formation of Seed in Optical Glass Melts," Jour. Amer. Ceramic Soc., Vol. I, 134 (1918).

Since both the appearance and disappearance of the seeds under these conditions is a process requiring a certain amount of time for the attainment of equilibrium, the viscosity of the glass, the time during which it is under the reduced pressure, and the subsequent cooling and annealing operations will evidently all have an influence on the final state of the glass as regards freedom from seeds. Seeds formed from glass which is supersaturated or practically completely saturated with dissolved gases cannot be removed by annealing, but seeds resulting from reduced pressure upon glass which is undersaturated with dissolved gases will disappear or be greatly reduced in size by proper annealing.

The complete story of the effect of dissolved gases upon the properties and behavior of glass must await the results of further investigation. It seems entirely probable that the presence of dissolved gases, and especially of microscopic seeds, may materially increase the tendency of the glass to devitrify, and the entire removal of this constituent might make it possible to obtain results which are not possible under ordinary conditions owing to the rapidity of devitrification. Certainly the known facts concerning the behavior of other supercooled solutions point in this direction.*

23. *The Use of Vacuum Furnaces in the Manufacture of Glass.*—The results described in the preceding pages are to be regarded as preliminary only. It is intended to continue the investigation not only for the purpose of determining the influence of dissolved gases upon the properties and behavior of glass, but also for the purpose of determining the practicability and value of a commercial process for the production of gas free glass.

The investigation of this subject was started early in 1918, and the results thus far attained indicate that a vacuum furnace process for the manufacture of certain types of glass is entirely feasible on an industrial scale, and that it offers a number of pronounced advantages over current methods. It eliminates entirely the fining operation as ordinarily understood, materially reduces the high finishing temperatures required with some glasses, produces in all cases a product absolutely free from even the smallest seeds, and these results suggest the possibility of considerably increasing the yield of perfect glass. Its main field of usefulness will probably be in the manufacture of certain types of optical glasses and of glass for high vacuum apparatus.

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* In this connection see Germann, A. F. O., "The Devitrification of Glass, a Surface Phenomenon. The Repair of Crystallized Glass Apparatus." Jour. Amer. Chem. Soc., Vol. 43, 11 (1921).

VII. SUMMARY

24. *Summary of Results.*—The results of the investigation to date may be summarized as follows:

(1) All varieties of glass in the finished state contain dissolved gases.

(2) The amount of this dissolved gas is sufficient to cause the glass to effervesce violently if the pressure upon it be suddenly reduced while it is in a fluid condition.

(3) The amount and composition of the dissolved gas varies greatly with the type of glass and the detail of the melting and fining procedures.

(4) In the three types of industrial glass examined, the volume of the dissolved gases (measured under standard conditions) varied from 0.2 to 2 times the volume of the glass itself.

(5) Carbon dioxide, oxygen, and nitrogen were found in varying amounts in the gas.

In addition, as a result of this experimental work, a convenient apparatus for measuring and analysing the dissolved gases was developed, and an improved type of vacuum furnace for the manufacture of gas-free glass was constructed.

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